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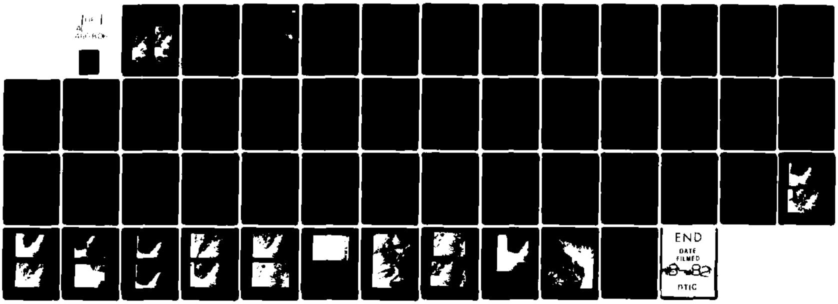

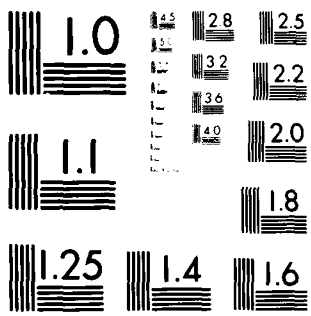

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Ice distribution and winter surface circulation patterns, Kachemak Bay, Alaska

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Cover: Landsat images of Kachemak Bay, Alaska. Left: Landsat-2 band 5 image 21288-20255, 2 August 1978; summer surface water patterns are visible because of the concentrations of suspended sediment discharged from glacial rivers. Right: Landsat-2 band 5 image 21484-20225, 14 February 1979; surface suspended sediment patterns not visible although ice is apparent at the upper end of the bay along the north shore and north of Homer Spit.

CRREL Report 81-22

Ice distribution and winter surface circulation patterns, Kachemak Bay, Alaska

Lawrence W. Gatto

December 1981

Prepared for
U.S. ARMY ENGINEER DISTRICT, ALASKA
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Development of the hydropower potential of Bradley Lake, Alaska, would nearly double winter freshwater discharge from the Bradley River into upper Kachemak Bay, and the Corps of Engineers is concerned about possible subsequent increased ice formation and related ice-induced problems. The objectives of this investigation were to describe winter surface circulation in the bay and document ice distribution patterns for predicting where additional ice might be transported if it forms. Fifty-one Landsat MSS band 5 and 7 and RBV images with 70% cloud cover or less, taken between 1 November and 30 April each year, were analyzed for the eight winters from 1972 to 1980 with standard photointerpretation techniques. Results of this analysis showed that glacial sediment discharged into Kachemak Bay acts as a

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natural tracer in the water. Inner Kachemak Bay circulation in the winter is predominantly counterclockwise, with northeasterly nearshore currents along the south shore and southwesterly nearshore currents along the north shore. Most of the ice in the inner bay forms at its northeast end and is discharged by the Fox, Sheep and Bradley Rivers. Some ice becomes shorefast on the tidal flats at the head of the bay, while some moves southwestward along the north shore pushed by winds and currents. When this ice reaches Coal Bay, it accumulates between Homer Spit and the north shore. This buildup extended out to Coal Point at the tip of Homer Spit in February 1976 and 1979; ice was not observed in the nearshore zone along the south shore of the inner bay. Most of the summer circulation patterns in the outer bay determined by previous drift card and current meter surveys and from temperature and salinity distributions were not observed on the winter imagery. Because the surface water of the outer bay is generally much clearer year-round than that in the inner bay and because ice is usually absent, winter surface circulation patterns could be inferred for only limited areas around the outer bay. No ice was observed anywhere in the entire bay on the November imagery and most of the ice was gone by mid-April. The ice distribution and generalized circulation patterns indicated that any additional ice formed in the inner bay due to future increased winter discharge from Bradley River would be likely to accumulate along Homer Spit and probably be blown into the outer bay by the dominant northerly winter winds.

PREFACE

This report was prepared by Lawrence W. Gatto, Research Geologist, of the Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was funded by the U.S. Army Engineer District, Alaska, under Intra-Army Order E-86-80-0038, *Prediction of Ice Growth and Circulation in Kachemak Bay, Bradley Lake Hydroelectric Project.*

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

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Multiply	*By*	*To obtain*
foot	0.3048*	meter
$foot^3$	0.02831685	$meter^3$
$foot^3$/second	0.02831685	$meter^3$/second
$mile^2$	2.589998	$kilometer^2$
mile/hour	0.4470400*	meter/second
knot	0.5144444	meter/second
degrees Fahrenheit	$t_{°C} = (t_{°F}-32)/1.8$	degrees Celsius

*Exact

ICE DISTRIBUTION AND WINTER SURFACE CIRCULATION PATTERNS, KACHEMAK BAY, ALASKA

Lawrence W. Gatto

INTRODUCTION

The Alaska District of the Corps of Engineers is currently planning to develop the hydropower potential of Bradley Lake, Alaska (Fig. 1). A dam will be located on the west end of the lake at the head of Bradley River. Reservoir water will travel through an underground tunnel, penstock, powerhouse and tailrace tunnel to be discharged onto the Kachemak Bay tidal flats (U.S. Army Engineer District, Alaska 1981). The current anticipated operating scheme of the power plant indicates that fresh water discharge from Bradley Lake into upper Kachemak Bay in the winter will greatly increase. Both local residents and the Corps are concerned that this increased volume of fresh water may cause additional ice to form in the bay and subsequently increase the icing problems that, to some degree, already exist.

In addition, the Corps is concerned about the possible impact of more ice on the bay's ecosystem, especially on intertidal organisms. Within a few miles of Kachemak Bay are located bays that have a heavy ice cover and significantly different ecosystems. The Kachemak Bay ecosystem is adapted to its present ice regime. A change in that regime may adversely affect the intertidal systems and related fisheries.

Kachemak Bay is very important to the local fishing industry. Commercial fishermen harvest king crab, tanner crab, dungeness crab, five species of Pandalid shrimp, five species of Pacific salmon, halibut, and herring from the bay, and it is a major spawning area for many types of fish. Kachemak Bay comprises less than 5% of the marine waters in the Cook Inlet Management Area, yet it produces on an annual basis over 60% of the area's total shellfish (Trasky et al. 1977). Regional fishery managers want to anticipate if Kachemak Bay will have more ice as a consequence of the Bradley Lake project.

The objectives of the research reported here are to describe existing winter surface circulation patterns and ice movement in the bay as analyzed from satellite imagery, to consider the effects of wind speed and direction on the observed patterns and ice movement, and to prepare a map showing circulation patterns under various observed wind conditions.

PHYSICAL SETTING

Kachemak Bay (Fig. 1), contiguous to southeastern Cook Inlet, is separated into inner and outer bays by four-mile-long Homer Spit. The north shore of the bay is bordered by rolling hills and the sand and clay bluffs of the Kenai Lowlands; the south shore is bordered by the Kenai Mountains. The coast along the north shore has mud flats with scattered rocks and boulders, while the south coast has mountainous, glacially eroded bedrock with sheltered passages, deep bays and several islands. The head of the bay has extensive tidal flats and low marshlands on a braided river floodplain.

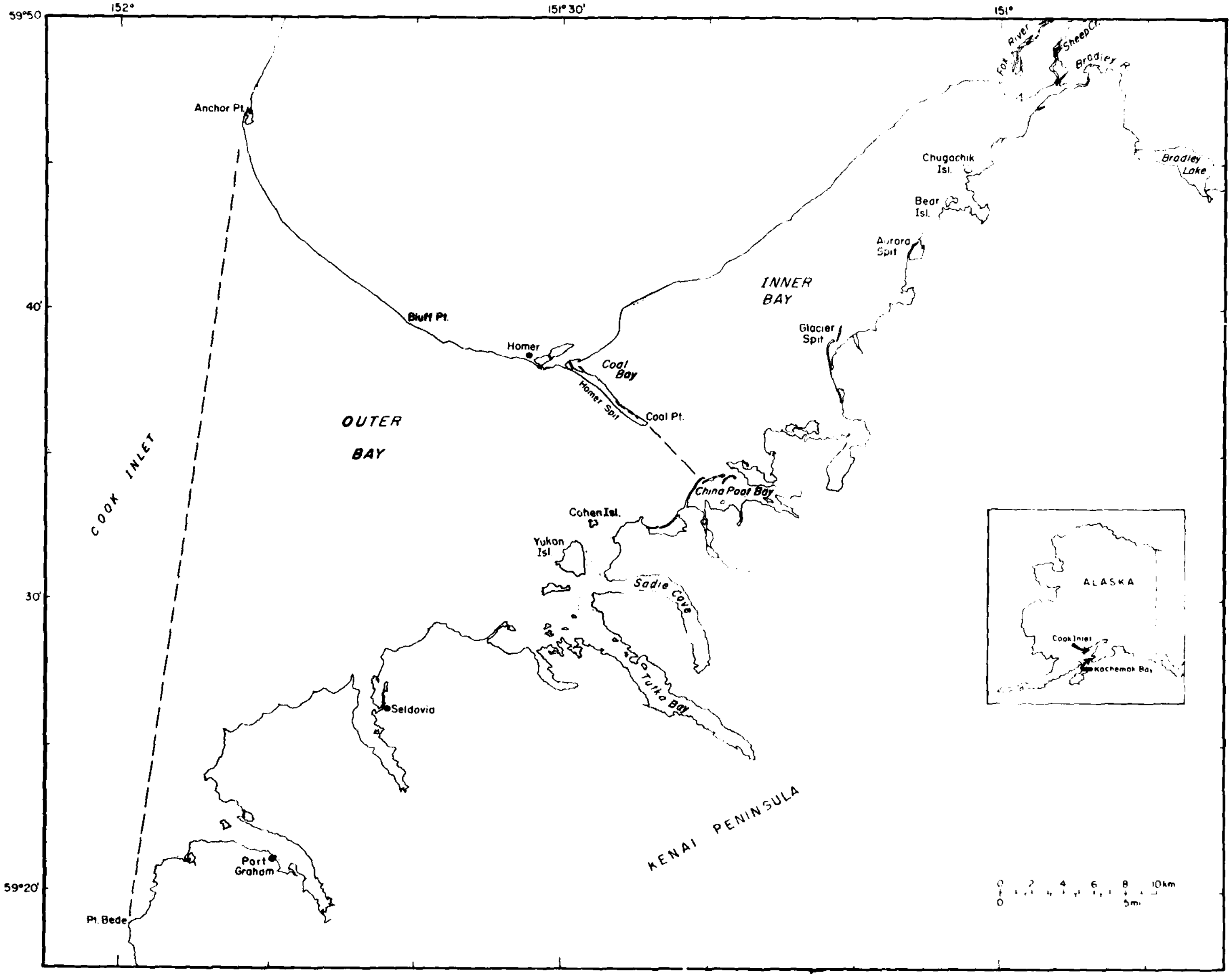

Figure 1. Location map, Kachemak Bay.

Hydrology

Eleven major glacial rivers and streams and 10 minor nonglacial streams drain the south shore of the bay. Eight small nonglacial streams drain the inner bay's north shore (Trasky et al. 1977). The drainage area of the Bradley River is about 92 mile², or 17.3% of the 530-mile² area draining into the upper end of the inner bay (U.S. Army Engineer District, Alaska 1975).

Based on USGS data from 1958–1973, average annual flow of the Bradley River is 1.25×10^{10} ft³. Of this, only 9.5% or 1.19×10^{9} ft³ is discharged from November to May (U.S. Army Engineer District, Alaska 1978). As winter progresses, surface flow ceases and ground water storage is the only contributor to flow. If the project is developed, the maximum discharge from the tailrace will be 1400 ft³/s*, equivalent to an early June to mid-August discharge.

Climate

Kachemak Bay is located between the mild maritime climate of the Gulf of Alaska and the seasonal extremes of interior Alaska. Cool summers, mild winters, moderate precipitation and frequent storms characterize the area. Summer average temperatures range from 42° to 59°F, and winter temperatures average from 17° to 42°F. Annual precipitation in Kachemak Bay averages 28 in. of rain and 101 in. of snow. Skies over Kachemak Bay are usually cloudy with an average of 229 cloudy days, 67 partly cloudy days, and only 69 clear days per year.

Wind speeds at Homer average 6.6 mph with extreme winds of up to 86–115 mph recorded. Storms with winds of 58–86 mph occur nearly every year (Evans et al. 1971). Average wind direction is from the north or northeast in winter and southwest in summer. Usually, average summer wind velocities (17–29 mph) are higher than in the winter. Figures 2–4 show winter wind characteristics from November through April. Predominant wind directions are from the northeast and north except in April, when winds are usually from the southwest or north-northeast. The vector mean winter wind is from the north-northeast at 3.1 mph (Table 1).

Bathymetry

Average depth in Kachemak Bay is 150 ft. The bottom of the Bay is gently sloping and relatively flat except for the 180- to 240-ft-deep trench along the south-central side. The deepest part of the bay is a 576-ft depression northwest of Cohen Island (Fig. 1).

Physical oceanography

Tides in Kachemak Bay are semi-diurnal. The differences between successive low and high waters are generally 2 to 6 ft. Mean diurnal range at Seldovia is 15.4 ft, at Port Graham, 14.4 ft, and at Homer, 15.7 ft. The highest tide at Seldovia is 22.9 ft and the lowest tide is about -6.0 ft (NOAA 1978).

Circulation is strongly influenced by fresh water runoff during the spring and summer; however, tides are a significant (and possibly controlling) driving force in the circulation of the inner bay. During the fall and winter, when runoff is low, circulation is tidally driven. The Coriolis force causes intensification of the surface outflow of fresh water along the northwest shore

Table 1. Winter wind summary, Homer, Alaska (from Brower et al. 1977).

	Frequency of wind speed ≤ 12 mph (%)	*Frequency of wind speed ≥ 39 mph (%)*	*Vector mean wind (mph)*	*Scalar mean wind (mph)*
November	30	10	NE at 3.1	19.6
December	35	15	NNE at 3.0	18.4
January	50	6	NE at 3.7	16.1
February	40	9	NE at 2.9	16.1
March	60	6	No data	11.5
April	55	5	SSW at 2.9	15.0

*Personal communication with S. Bredthauer, Alaska District, 1980.

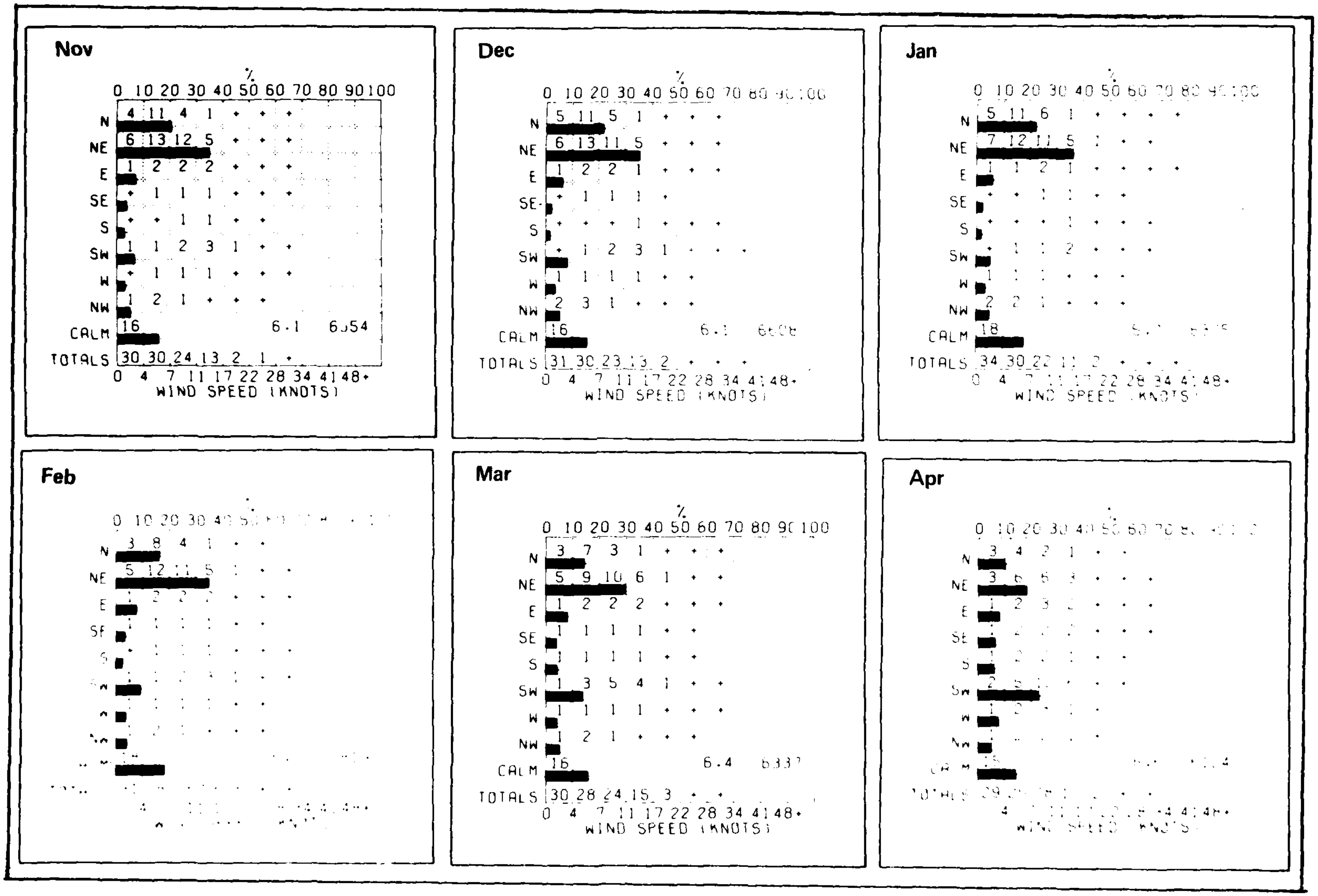

Figure 2. Wind speed and direction at Homer (from Brower et al. 1977, see App. A for legend).

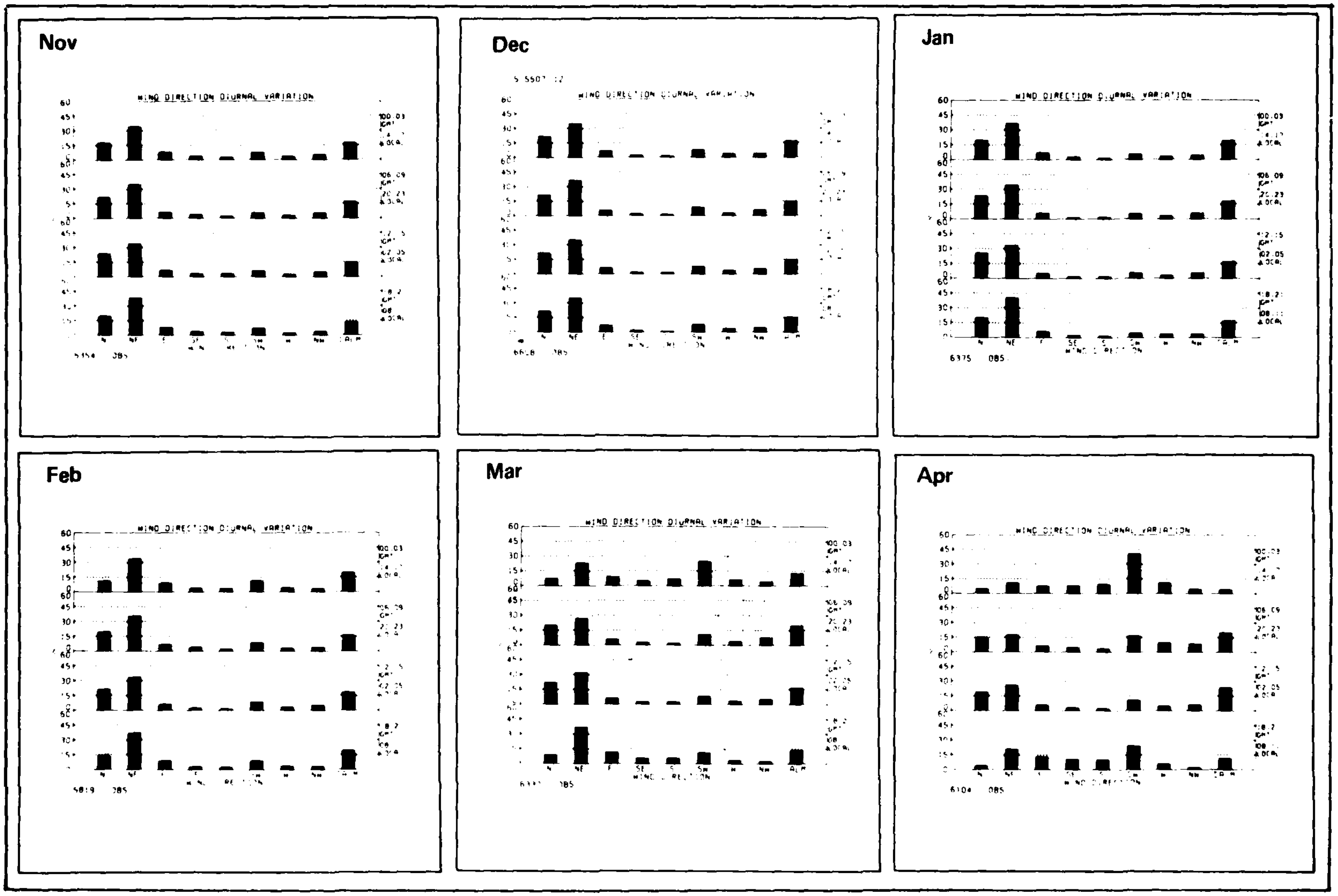

Figure 3. Wind direction and diurnal variation at Homer (from Brower et al. 1977, see App. A for legend).

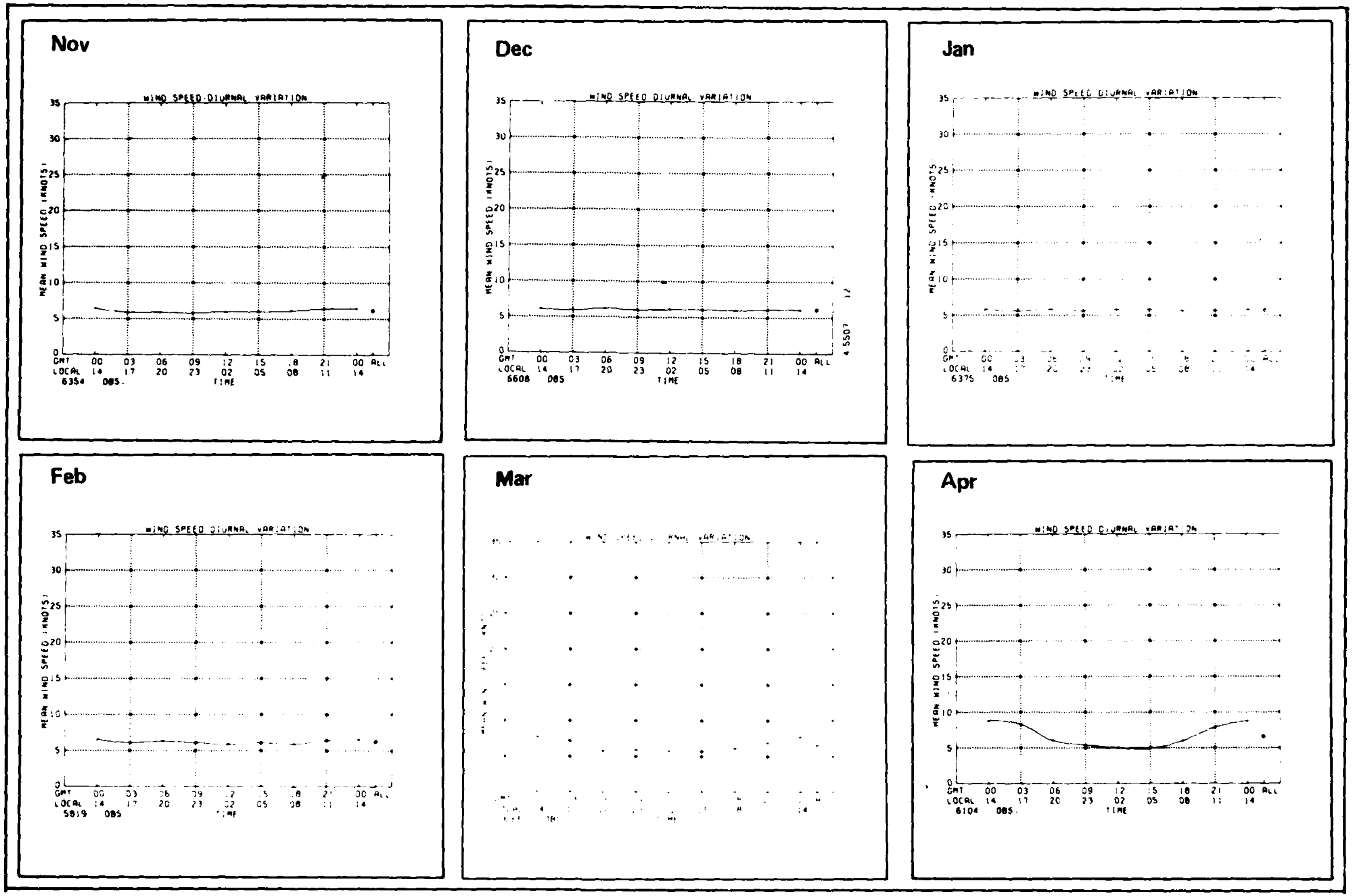

Figure 4. Wind speed and diurnal variation at Homer (from Brower et al. 1977, see App. A for legend).

and of deep water inflow along the southeast coast. The formation of two counterclockwise gyres in the inner bay is probably enhanced by the coastal and bottom morphology of the inner bay (Burbank 1977).

The dominant water movement in Kachemak Bay is the oscillatory flood and ebb of the tide. The net circulation in the outer bay is independent of, but largely driven by, tidal currents and is characterized by an influx of clear ocean water from the Gulf of Alaska on the south side of the bay and a corresponding outflow of water on the north side of the bay. This general northward flow is interrupted in the central region of the outer bay by two semipermanent gyres (Trasky et al. 1977).

Although fed in part by glacial streams, outer Kachemak Bay waters generally have a lower suspended sediment load than water in the inner bay. This difference is increased in spring and summer due to glacial and river runoff near the head of the inner bay. During spring and summer, the relatively fresh, silt-laden waters are carried out of the inner bay along the northwest shore, discharged into the outer bay, and subsequently carried northwest along the northern shore of the outer bay (Gatto 1976, Trasky et al. 1977). Eroding bluffs along the north side of the inner and outer bays and erosion along Homer Spit contribute additional sediments (Gronewald and Duncan 1965, Trasky et al. 1977).

Inner Kachemak Bay is a positive estuary where precipitation and fresh water input exceed evaporation (Burbank 1977). There is a net outflow of low salinity surface water from the inner bay past the tip of Homer Spit and into the outer bay (Trasky et al. 1977). The inner bay is also a partially mixed estuary characterized by vertical tidal mixing of the fresh surface waters with underlying saline waters (Burbank 1977).

Wind effects on circulation

Seasonal storms strongly influence outer bay circulation. September observations show that strong southerly winds persisting more than 1 to 2 days will intensify northerly water flow in the outer bay, eliminate the gyres and produce a strong net northward flowing current throughout outer Kachemak Bay (Burbank 1977).

The effects of persistent strong winds from other directions were investigated during 1974 drift card studies that suggested a regional east or southeastward transport of surface waters into the Kachemak Bay region commencing in early October. Such surface transport might be induced by strong west or northwesterly winds; however, accurate weather data for southern lower Cook Inlet are not available for this period (Burbank 1977).

Strong northerly storms common during the winter could be expected to generate strong, southward-flowing surface currents throughout lower Cook Inlet. Circulation within Kachemak Bay will be affected during all variations in central lower Cook Inlet circulation, but the exact effects within Kachemak Bay (for winds other than southerly) cannot be predicted from existing information (Burbank 1977).

Strong winds have been observed to exert a significant effect on the surface circulation in the inner bay. The response of inner bay surface waters to wind stress is considerably more rapid than observed in the outer bay. Subsurface waters are also accelerated in the direction of the surface waters, but to a lesser degree (Burbank 1977).

PREVIOUS INVESTIGATIONS

Because of the potential development of the petroleum resources in the lower Cook Inlet area, several studies of the circulation in lower Cook Inlet including outer Kachemak Bay have been made. Gatto (1976) and Muench et al. (1978) analyzed current, salinity and temperature data obtained from May to September 1973 and concluded that a clockwise gyre exists in the summer between Anchor Point and Point Bede in the lower inlet. Hein et al. (1979) used clay-mineral distribution patterns to infer circulation in Cook Inlet and the northwestern Gulf of Alaska. Shearman (1980) summarized some of the investigations that used radar to measure estuarine currents and showed surface currents in the outer bay. Barrick (1978), Barrick et al. (1979) and Frisch and Weber (1980) used Doppler radar to measure tidal currents in the summer. Their results show maps of circulation in the outer bay, velocity components of the currents, and the influence of the prevailing southwesterly summer winds. They concluded that bottom topography in the outer bay diverts a portion of the northerly flowing flood water into the bay.

Science Applications, Inc. (1977) summarized some existing information, reporting a quasi-permanent clockwise gyre (Fig. 5) in the outer bay and a typical estuarine two-layered structure in the water column of the inner Kachemak Bay. Knull and Williamson (1969) reported that this

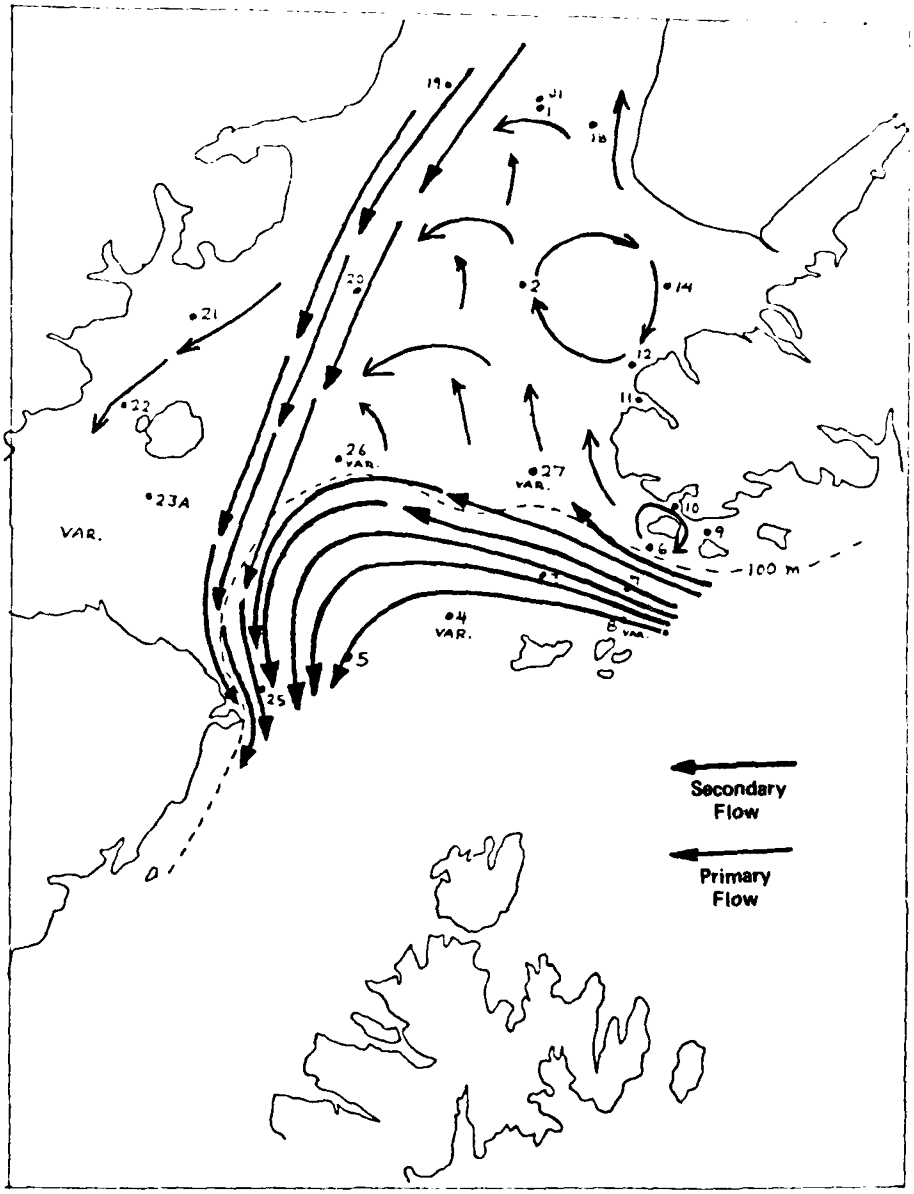

Figure 5. Lower Cook Inlet flow regime as derived from hydrographic and current data obtained during summer 1973 (from Science Applications, Inc. 1977).

stratification is at a maximum in July when runoff is high while Gatto (1976) suggested that stratification weakens in late spring and early fall when fresh water inflow is reduced.

Additional investigations addressed the circulation in the inner and outer Kachemak Bay. Burbank (1977) reviewed many previous studies of the bay circulation. Gatto (1976) used satellite imagery, aerial photography, NOAA data and the orientation of spits and bars to infer surface circulation in Kachemak Bay. He reported that a predominant nearshore flow continues counterclockwise around the bay north shore. Knull and Williamson (1969) estimated flood currents past the mouth of the bay to be 5 knots. Trasky et al. (1977) reported that the net circulation in the outer bay is characterized by an influx of clear ocean water from the Gulf of Alaska on the south side of the bay and a corresponding outflow of water on the north side. The general

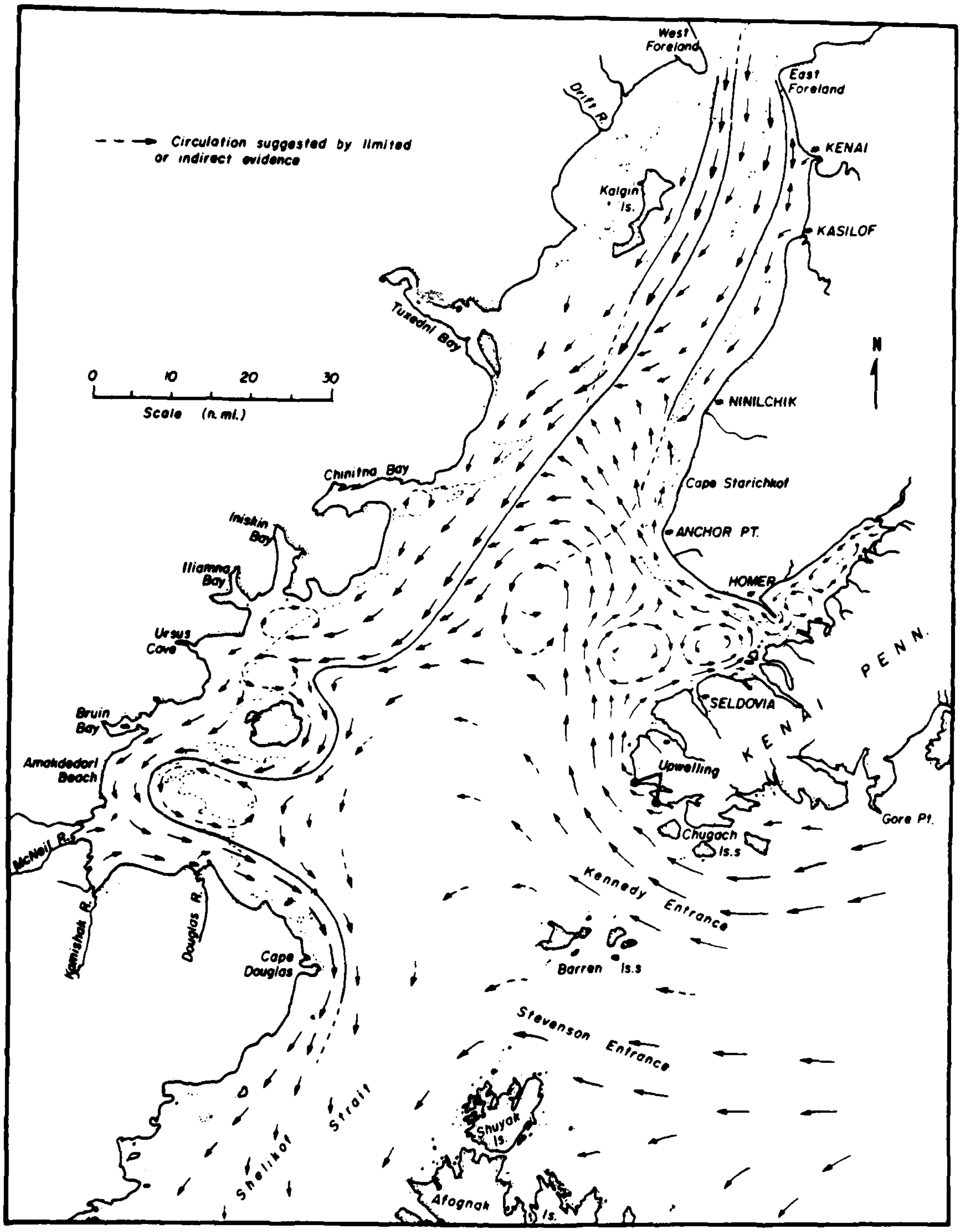

Figure 6. Net surface circulation in Lower Cook Inlet, based primarily on data collected during the spring and summer seasons (from Burbank 1977).

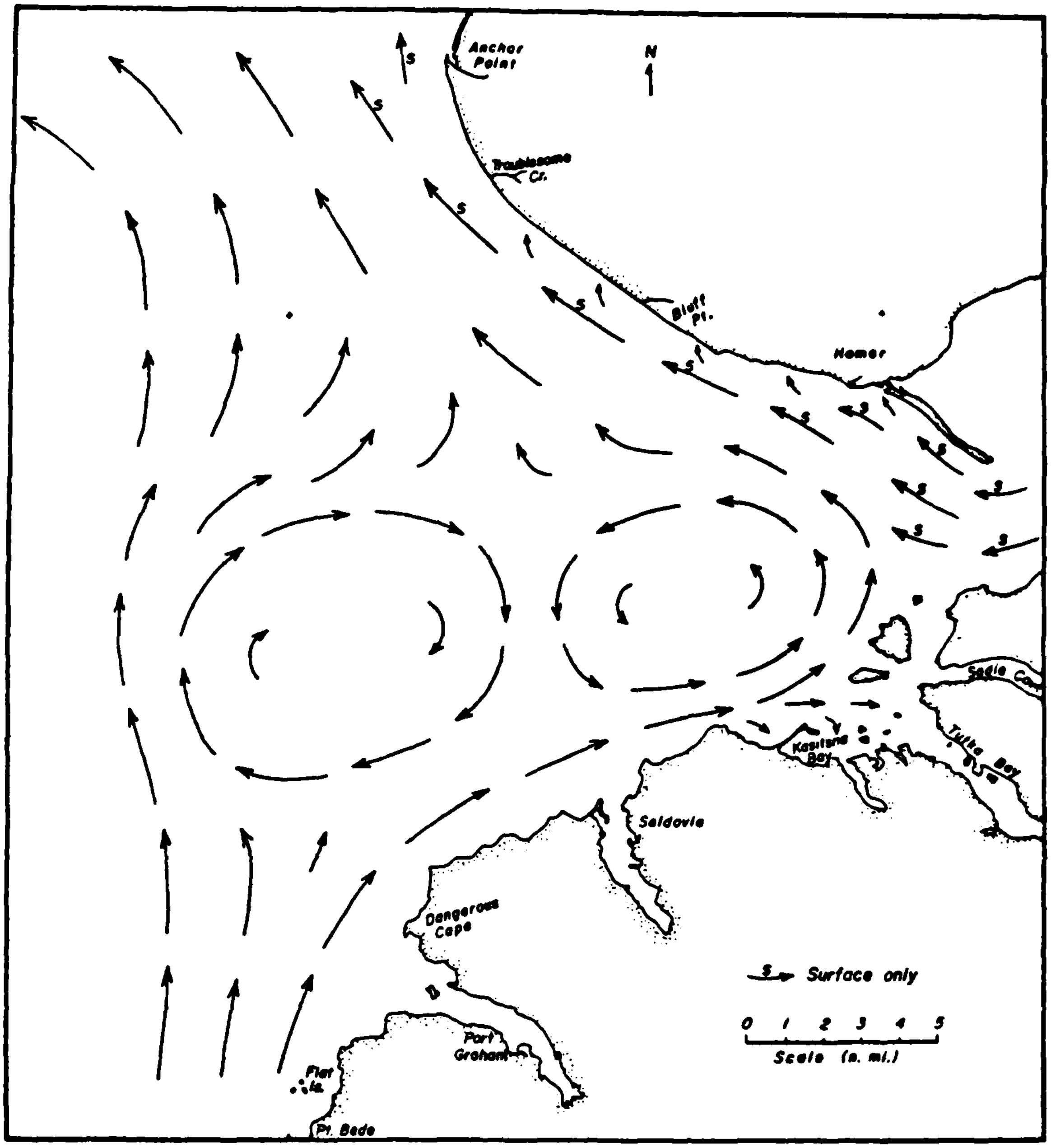

Figure 7. Net surface and subsurface (50–100 ft) circulation in outer Kachemak Bay (from Burbank 1977).

northerly flow is interrupted in the middle of the outer bay by two semipermanent gyres. Trasky et al. (1977) also reported that the outer clockwise gyre migrates north and south with the flood and ebb tides because the oscillatory tidal movements dominate the net circulation.

Colonell (1980) traced rhodamine WT dye dispersion by making vertical and horizontal fluorometer measurements in late August, early October and mid-November 1980. Dye releases were made in the Bradley River, and the measurements were taken in the Bradley River estuary at the head of the inner bay. Results show that tidal mixing of fresh river water and saline bay water in the estuary is nearly complete after three tidal cycles and that the Bradley River water spreads from the estuary to Chugachik Island along the south shore after two tidal cycles.

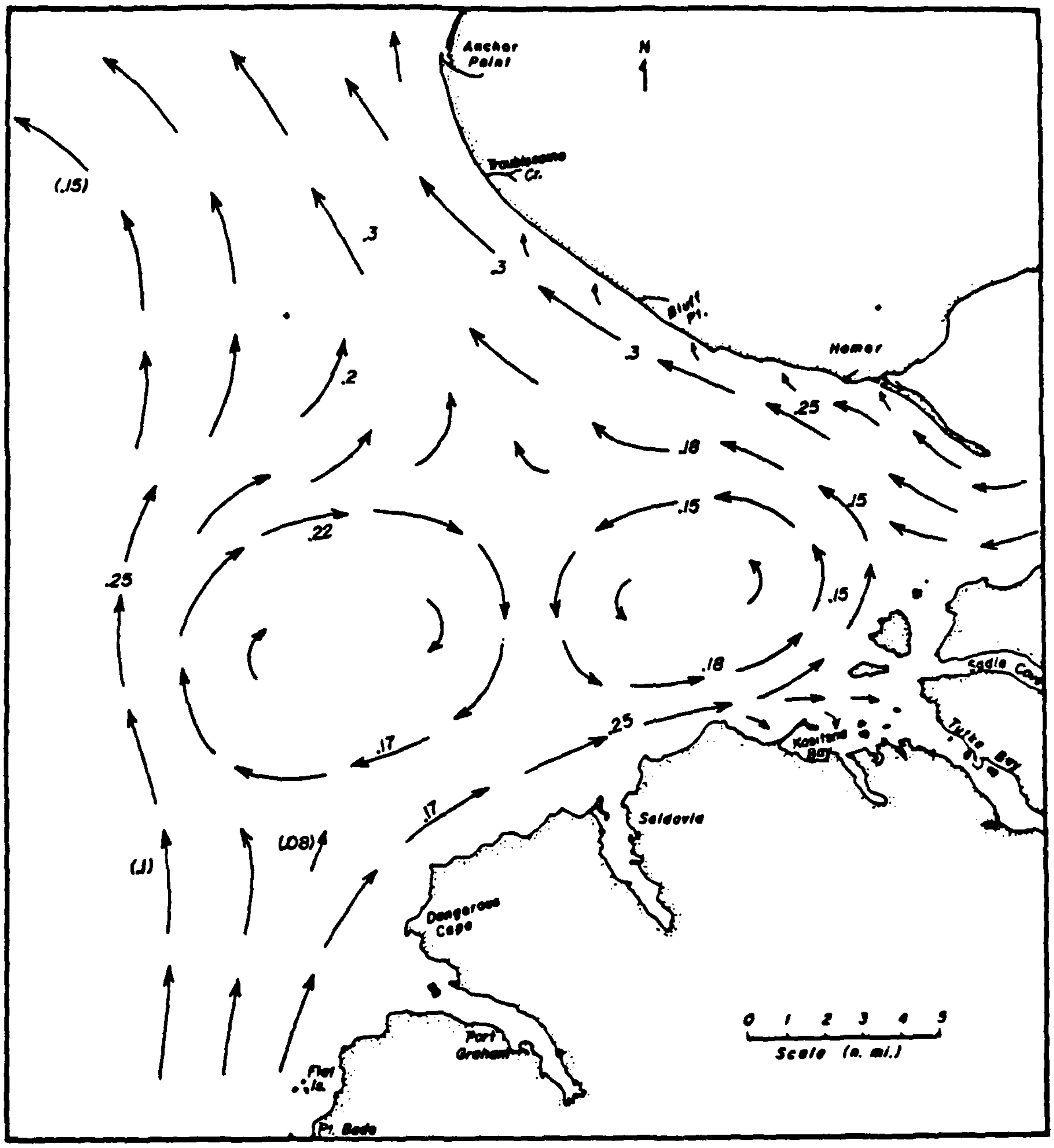

Figure 8. Net surface circulation in outer Kachemak Bay with typical net surface current velocities (knots) indicated for various areas in the bay (1 kt = 1.15 mph); parentheses indicate where the velocity was determined from only one period of observation (from Burbank 1977).

He concluded that increased flows of the Bradley River in the winter may result in the production of more ice along the south shore, northeast of Chugachik Island.

Burbank (1977) used radar-tracked drogues, drift card studies, general marine observations of surface drift patterns and Landsat imagery interpretations to construct the generalized circulation of lower Cook Inlet and Kachemak Bay (Fig. 6). He found that the surface and subsurface circulation patterns change seasonally from 27 May to 17 November 1975 and from 8 March to 22 September 1976. He also reported that surface currents in particular were changed continually by fresh water runoff, tidal influences and winds. In spite of these dynamics and resulting changes, there was a net circulation pattern that persisted (Fig. 7–9).

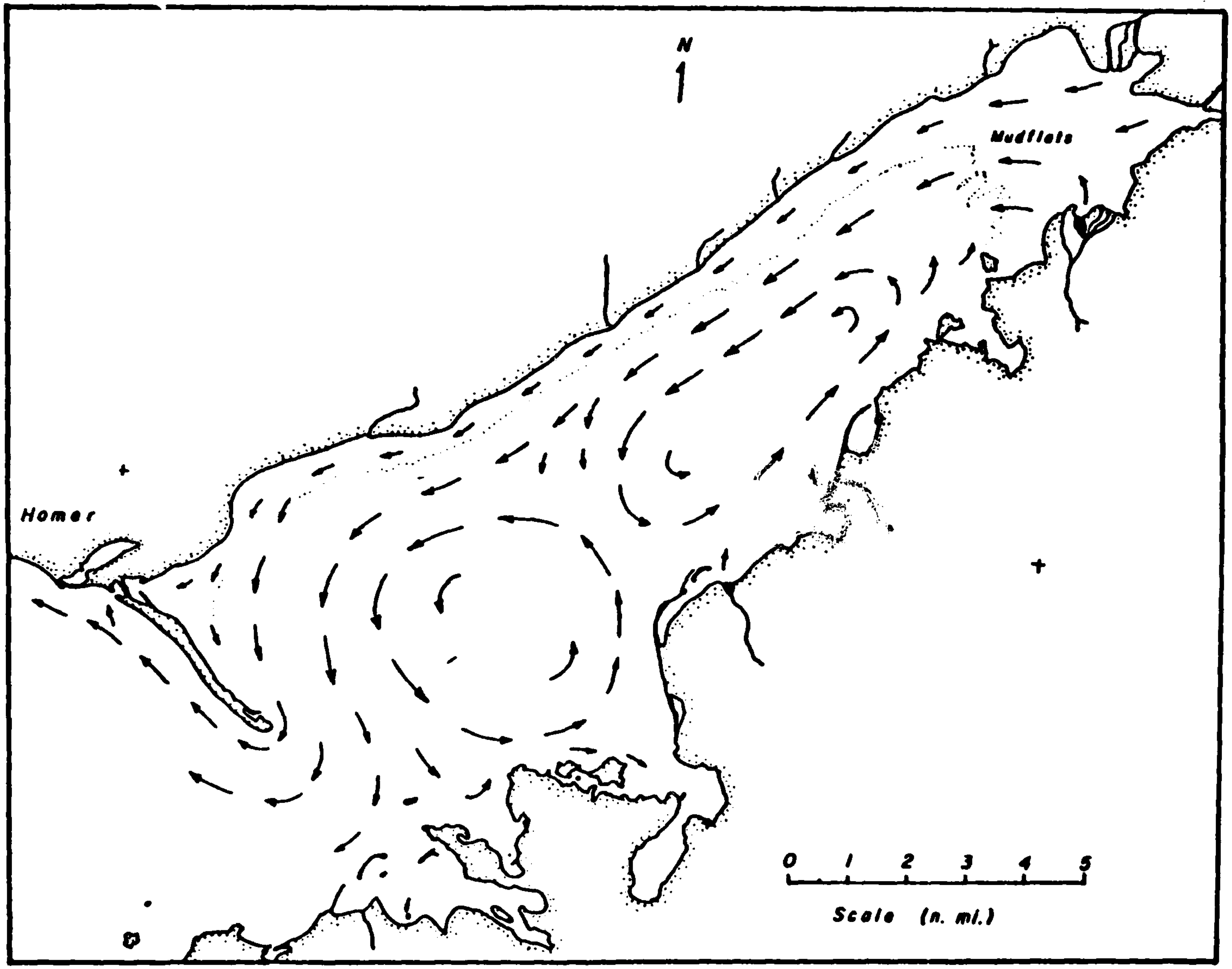

Figure 9. Surface currents in inner Kachemak Bay (from Burbank 1977).

The opposing currents of several of the adjacent gyres and flows shown in Figures 6-9 probably do not reflect net or mean circulation patterns as suggested by Burbank (1977) but rather currents that can be observed and measured but do not persist. These flows are found in inner Kachemak Bay (Fig. 6), along the south shore in the outer bay west of Seldovia, in the central southern Cook Inlet southwest of Anchor Point and in Kamishak Bay northwest of Cape Douglas.

Burbank (1977) pointed out that there may be a bias in his mapped circulation patterns since much of his data were collected in the spring and summer when fresh water runoff is moderate to high and winds are generally moderate and southerly. During the winter, fresh water runoff is low to negligible and winds are typically strong northerlies. He concluded that major changes in bay circulation patterns are comparatively infrequent during the more quiescent spring and summer. Beginning in September and continuing through the winter, strong seasonal storms frequently alter this circulation.

APPROACH

Imagery analyzed

Only satellite imagery obtained between 1 November through 30 April was used in this study since winter circulation patterns were being analyzed. Table 2 shows the sources contacted and the availability of imagery. Winter aerial photography and satellite imagery from Seasat, Nimbus-7 CZCS, HCMM and DMSP are

Table 2. Winter imagery available for Kachemak Bay.

Imagery Type	*Source*	*Remarks*
Aerial photography	EROS Data Center	None
	Northern Remote Sensing Laboratory, University of Alaska	None
	Air Photo Tech, Anchorage	None
	Corps of Engineers, Alaska District	None
Satellite imagery		
GOES	NOAA—NESS, Satellite Data Services Division	Yes
TIROS—N	NOAA—NESS, Satellite Data Services Division	Yes
NOAA—6 (NOAA series)	NOAA—NESS, Satellite Date Services Division	Yes
Nimbus-7 CZCS	NOAA—NESS, Satellite Data Services Division	None
Seasat	NOAA—NESS, Satellite Data Services Division	None
HCMN	GSFC—National Space Science Data Center	None
Nimbus series	NOAA-NESS, Satellite Data Services Division	Yes
Landsat	EROS Data Center	Yes
DMSP	University of Wisconsin	None

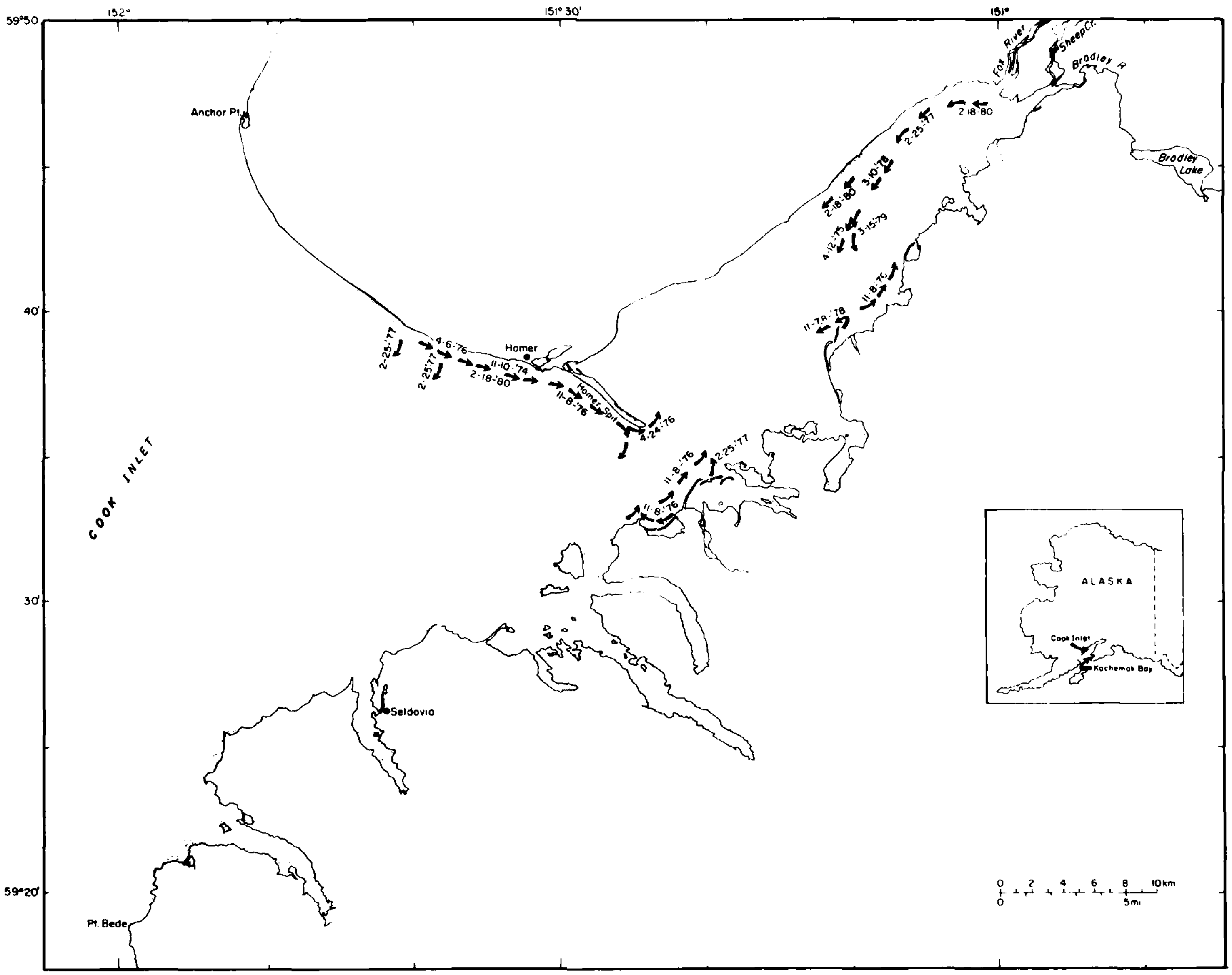

Figure 10. Inferred circulation based on suspended sediment patterns observed on Landsat imagery.

Table 3. Dates of usable Landsat imagery available between 1 November and 30 April 1972 to 1980.

1972-1973	*1973-1974*	*1974-1975*
2,3,4 November	16 November	10,12 November
8 March	3,4,22 March	10,27,28 February
15 April	26,27 April	16 March
		3,12 April
1975-1976	***1976-1977***	***1977-1978***
26 January	8,10 November	4,5 November
14 February	25 February	2 February
6,8,24 April	2 April	10,18 March
		5,7 April
1978-1979	***1979-1980***	
7,8,16,17 November	31 January	
5,6,7,14,23 February	18 February	
15,23 March	14 April	
11 April		

not available for the bay. Imagery from GOES, TIROS-N and NOAA and Nimbus series satellite are available, but they were not useful for this study because of their small scale.

Landsat imagery proved to be the only imagery available and useful. All MSS band 5 and 7 imagery and available Landsat-3 RBV and MSS band 8 (thermal IR) imagery with 70% or less cloud cover taken between 1 November and 30 April (Table 3) were analyzed using standard photointerpretation procedures. Imagery as received from the EROS Data Center was used without special computer enhancement or analysis.

The imagery from the eight winters was distributed as follows: 16 dates in November, none in December, two in January, 17 in February, 12 in March and 16 in April. Frequent cloud cover and the low sun angle in December and January drastically reduced the number of images available.

Wind and tidal data

Wind data from the National Climatic Center and tidal predictions from the National Ocean Survey were compiled so that descriptions could be made of the possible influences of the wind and tides on surface circulation.

RESULTS

Glacial sediment discharged into Kachemak Bay acts as a natural tracer in the water. However, glacial sediment and water discharges are low during the winter and the suspended sediment distribution in the surface water of the bay is much less obvious than in the spring and summer. In spite of this decrease, sufficient sediment and ice patterns were observable in the imagery to infer some generalized surface circulation patterns. Appendix B summarizes the observations made from the usable Landsat imagery.

Suspended sediment patterns

Circulation inferred from suspended sediment distribution (Fig. 10) was based on limited imagery observations. Sediment patterns were observable on imagery from 11 separate dates over eight winters. Suspended sediment distribution in the outer bay was apparent on the imagery only along the north shore and part of the south shore.

The patterns (Fig. 10) suggest counterclockwise circulation in the inner bay similar to that determined by Burbank (1977) for the spring, summer and fall (Fig. 9). However, there are some major differences from Burbank's (1977) observations. The inferred winter currents showed a southeasterly flow between Bluff and Coal Points on four separate dates. Other observations of the net littoral drift of beach sediments, suggesting nearshore circulation in the vicinity of Homer Spit, are similar to those shown in Figure 10*. Northeasterly flowing water was observed west of China Poot Bay. The two counterclockwise gyres in the inner bay (Fig. 9) were not apparent, although the sediment patterns

*Personal communication with T. Munsey, Office of the Chief of Engineers, 1981

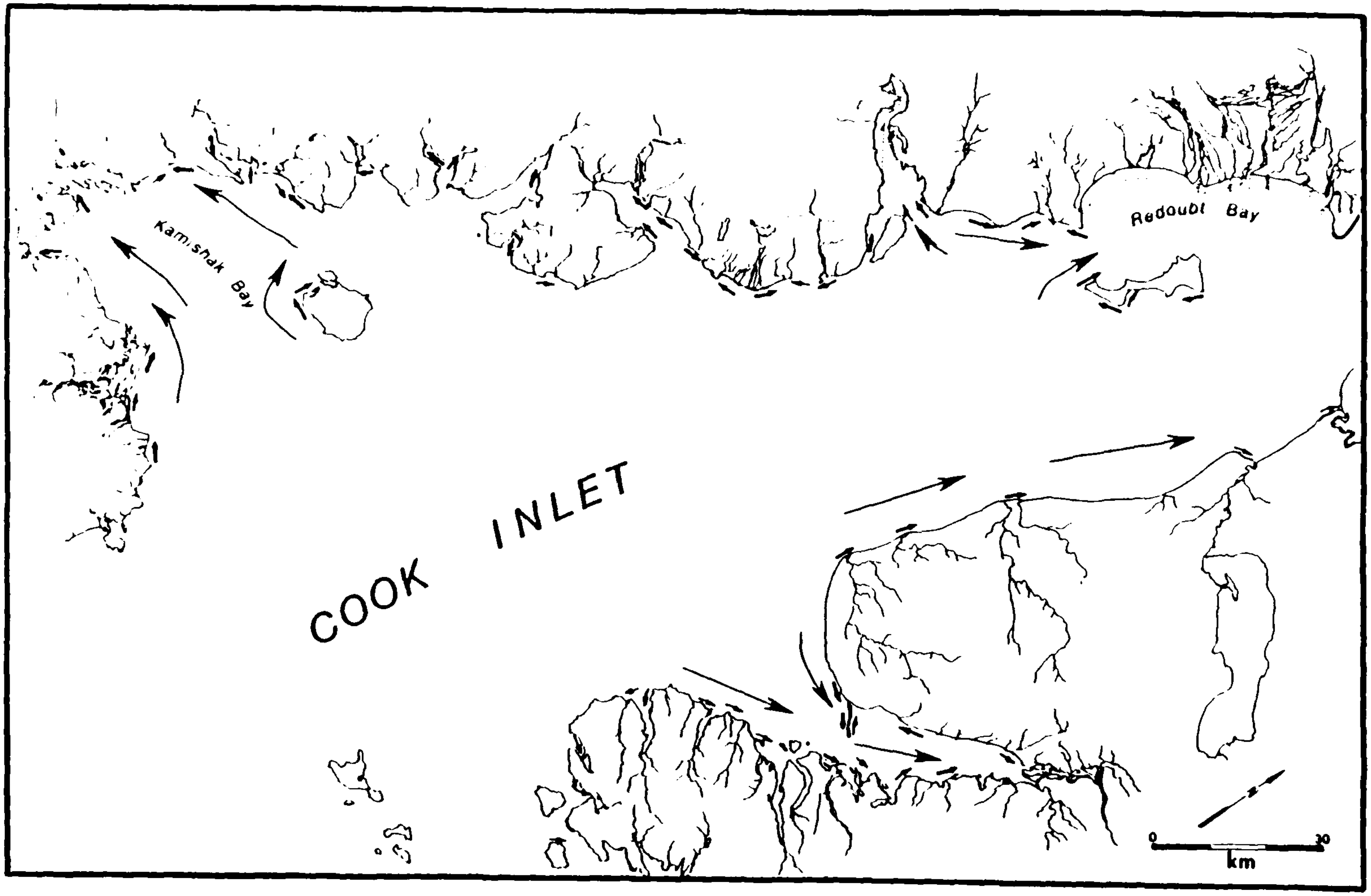

Figure 11. Longshore sediment transport patterns in lower Cook Inlet (from Trasky et al. 1977).

suggest that the northeastern gyre persists in the winter.

The amount of water flowing into the inner bay from the outer bay during flood tide in the winter may be larger than in the spring and summer. The volume of fresh water discharged into the inner Bay is lower in the winter, and since the volumes of the tidal prisms in the summer and winter are the same, more outer bay water must move into the inner bay to make up for the reduced fresh water input. Although intrusion of surface waters into inner Kachemak Bay was never observed during the drift card and drogue studies (Burbank 1977), this reduction of river fresh water input into the inner bay during winter allows more flow exchange between the outer and the inner bay.

A surface drogue placed at the entrance to the inner bay during November 1975 remained in the same vicinity for about one week, indicating little or no net surface circulation into or out of the inner bay at that time (Burbank 1977). However, the drift card studies by Bright et al. (1960) suggest occasional transgression of outer bay surface waters into the inner bay, although the time of year in which this occurred is not indicated. From observations of the configuration of the orientation of some of the coastal landforms (i.e. recurved spits, cuspate spits and beach protuberances) and the general trend of coarse-grained sediment transport by wave-induced longshore currents, Trasky et al. (1977) have indicated that flow into Kachemak Bay and the smaller embayments occurs frequently (Fig. 11).

No suspended sediment patterns were apparent on the Landsat imagery along the south shore of the outer bay west of Cohen Island or in the middle of the bay because the water is too clear in the winter. In addition, the two gyres and the other surface circulation patterns reported by Burbank (1977) were not apparent.

The effects of wind on surface water movement are not clear from the observed suspended sediment distribution and wind data. Winds on the day of and the day preceding Landsat image acquisition are shown in Table 4. The southwesterly current along the north shore of the upper inner bay was observed when winds had shifted from the southwest at 12.1 mph, to the SE-SSE at 14.4 mph and to the NNE at 9.1 mph. Likewise, the southeasterly current between Bluff Point and Coal Point was observed when winds shifted from the NNE at 8.1 mph, to the SE-SSE at 14.4 mph, to WSW at 13.8 mph, and to the SW-WSW at 6 mph. One would expect to observe this current most frequently when winds are from the SW to NW quadrant. Usually winter winds are from the N or NE. The currents along the south shore near the spit and farther into the inner bay (Fig. 10) were observed with winds primarily from the south and southeast.

Ice distribution

From December to March, floe ice in Cook Inlet often extends as far south as Anchor Point on the eastern side (Trasky et al. 1977, Gatto 1976). Although fast ice has extended up to three miles off the northern shore of the inner Kachemak Bay in severe winters, ice seldom forms in the outer bay because of the moderating influence of the Gulf of Alaska waters. During severe winters, icing problems occur in the inner bay, when ice from the head of the bay is blown against the Homer Spit by northerly winds (Trasky et al. 1977). The dock and boat harbor entrance are on the north side of the spit facing the inner bay and are directly affected by this wind-blown ice.

No ice was observed anywhere in Kachemak Bay in the November imagery and most of the ice was gone by mid-April. Ice distribution in Kachemak Bay as observed on 10 usable Landsat images from four years was usually limited to the inner bay. The ice near Anchor Point was observed frequently but it did not move into the outer bay. However, some ice appeared to move from the inner to the outer bay around Homer Spit.

Ice was concentrated at the head, along the north shore, and northeast of Homer Spit in the inner bay. Most of the ice in the inner bay is introduced into the bay by, or forms at, the mouths of the Fox, Sheep and Bradley Rivers on the northeast end (Fig. 12). Some ice becomes shorefast on the tidal flats at the head of the bay, while some is pushed southwestward along the north shore by winds and currents. When this ice reaches Coal Bay, it accumulates between the spit and the north shore. In February 1976 and 1979 this buildup extended out to Coal Point as shown on the Landsat imagery. An area of about 10.5 $mile^2$ in Coal Bay appeared ice-covered on 14 February 1976. Ice was not observed in the nearshore zone along the south shore of the inner bay except at the northeast end. These ice patterns suggest counterclockwise nearshore circulation in the inner bay.

Wind appears to more directly affect ice movement than water surface currents. The size and orientation of the inner bay, and the general type of ice in it indicate that wind data taken 12

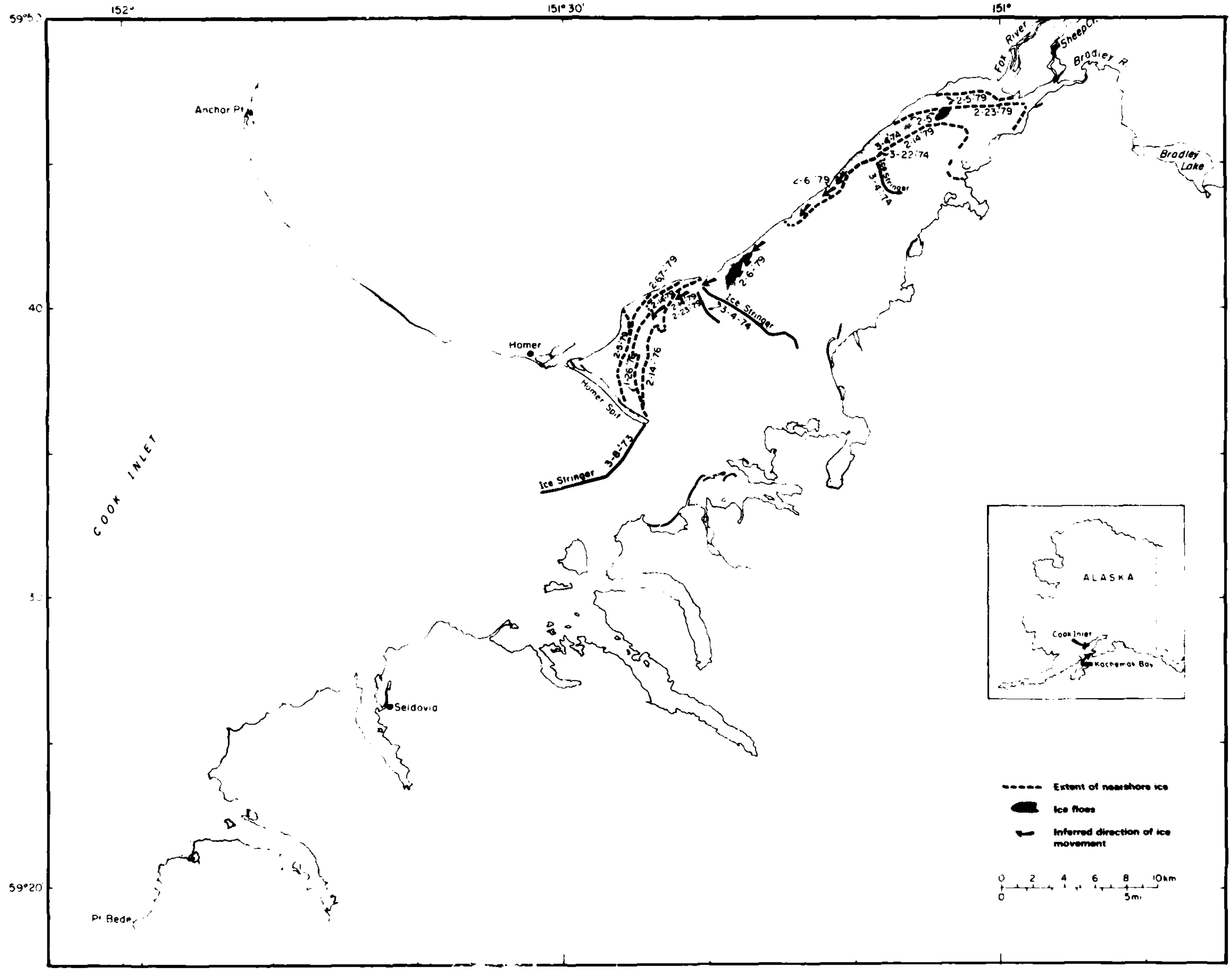

Figure 12. Ice distribution and movement as observed on Landsat imagery.

Table 4. Tidal stage and winds.

Image acquisition date	Tidal stage*	Winds** Day of imagery acquisition: Resultant direction	Avg. speed (mph)	Day before imagery acquisition: Resultant direction	Avg. speed (mph)
8 Mar 73	early flood	WSW	4.8	ENE	1.3
4 Mar 74	early ebb	WNW	14.2	WSW	21.9
22 Mar 74	mid- to late-flood	NNW to N	5.2	SSE	9.4
10 Nov 74	high water	E to ESE	10.4	NNE	7.7
12 Apr 75	mid-flood	SW	12.1	SW	10.5
26 Jan 76	early ebb	NE to ENE	6.5	NE	12.1
14 Feb 76	mid- to late-flood	N to NNE	3.3	NE to ENE	6.5
6 Apr 76	late ebb	SW to WSW	6	NE	7.1
24 Apr 76	high water	WSW	13.8	SW to WSW	5.8
8 Nov 76	mid-flood	S	11.9	SE to SSE	12.7
25 Feb 77	late ebb	NNE to NE	8.1	SE to SSE	14.4
10 Mar 78	early to mid-flood	SW to WSW	1.7	NNE to NE	7.2
7 Nov 78	mid- to late-flood	—	—	—	—
8 Nov 78	mid-ebb	—	—	—	—
5 Feb 79	early to mid-ebb	NE to ENE	10.9	—	—
6 Feb 79	early ebb	NE	8.3	NE to ENE	10.9
7 Feb 79	high water	NE	16.5	NE	8.3
14 Feb 79	early flood	NE to ENE	14.3	NE	8.2
23 Feb 79	high water	NE	4.3	NE to ENE	5.8
15 Mar 79	early to mid-flood	WSW to W	10.9	ENE to E	3.6
18 Feb 80	early to mid-flood	NE	9.1	—	—

*Predicted tides for the Seldovia station at the time of image acquisition, 1015-1045 hr.

**Homer Federal Aviation Administration, Alaska, National Weather Service monthly summaries.

—No data

hours to one day prior to an observed ice pattern would be sufficient to include the winds that had an influence in producing that pattern*. Therefore the National Weather Service wind data were summarized (Table 4) to determine winds on the day of and on the day preceding image acquisition.

When ice was observed along the northern shore, winds were predominantly from the N to NE, the normal winter wind direction. The ice appeared to accumulate on the tidal flats at the head of the inner bay even when winds were primarily from the NE to ENE. The dominant wind directions during and preceding the dates of ice accumulation in Coal Bay were NE to ENE, which is no surprise since such winds would push ice down the northern portion of the inner bay to the spit. The amount of ice deflection to the right of a pushing wind is probably less than 30°.* This deflection would be unimportant when compared to the ice pushed down the north shore by the northeasterly winds. The ice eventually covers Coal Bay and accumulates seaward.

*Personal communication with G. Ashton, CRREL 1981.

Ice stringers (Fig. 12) were observed on two dates. Both times, winds were from the western quadrant on the date the imagery was taken. The inner bay stringers (4 March 1974) were probably formed by strong (14.2- to 21.9-mph) westerly winds, pushing ice bayward from the north shore. The shape of the eastern end of the stringers suggests that they extended across the bay to the northeasterly currents in the southeastern portion of the inner bay.

The stringer extending from Coal Point was observed when the winds were from the WSW on the day of acquisition and from the ENE on the preceding day. Possibly the stringer was formed by ice pushed out of the inner bay past Coal Point and then deflected northward by the WSW winds.

Generalized surface circulation

The generalized winter surface circulation, as inferred from suspended sediment patterns and ice distribution, is shown in Figure 13. Inner Kachemak Bay circulation in the winter is predominantly counterclockwise with northeasterly nearshore currents along the south shore and southwesterly nearshore currents along the north shore. Local counter-currents were occa-

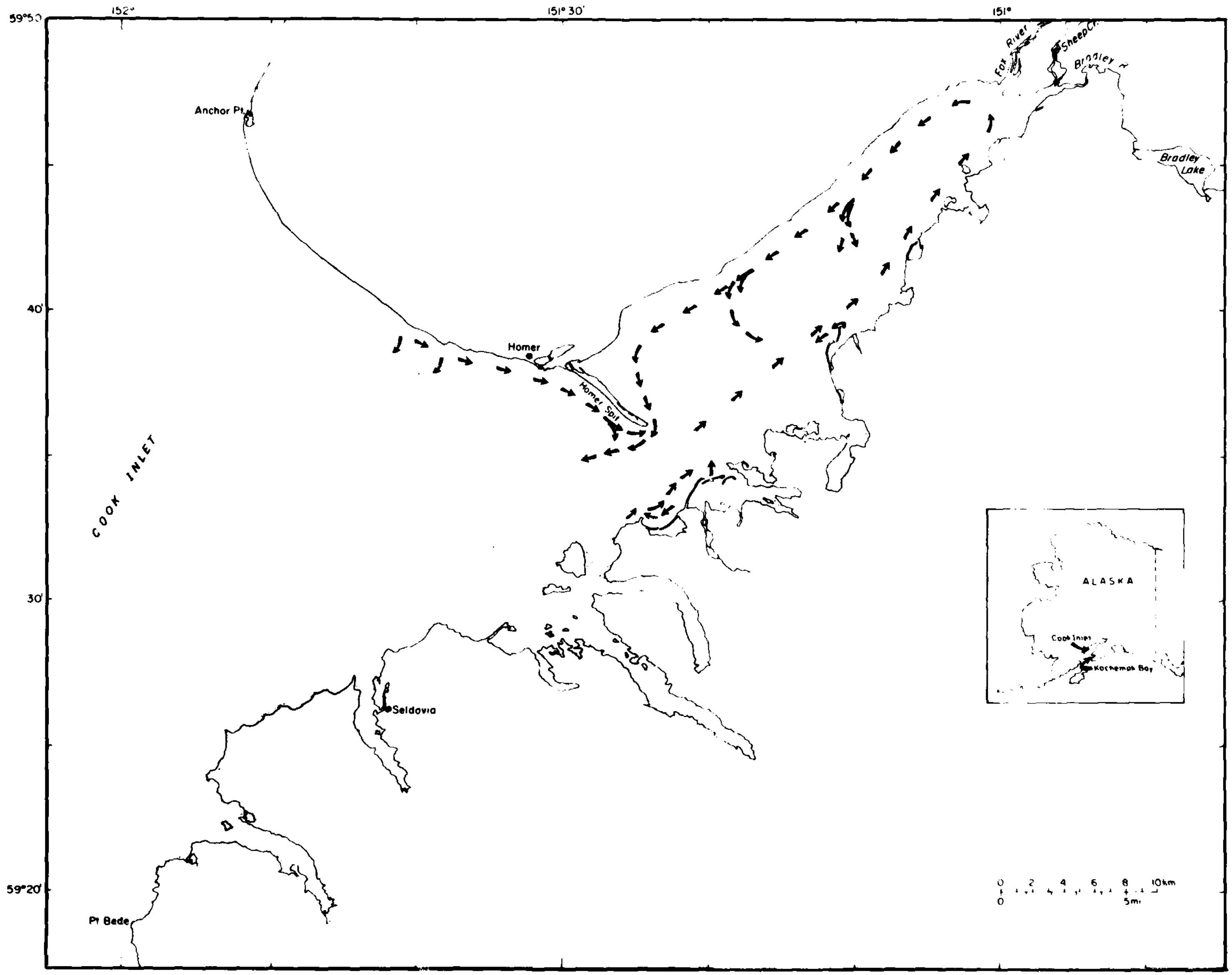

Figure 13. Generalized winter surface circulation.

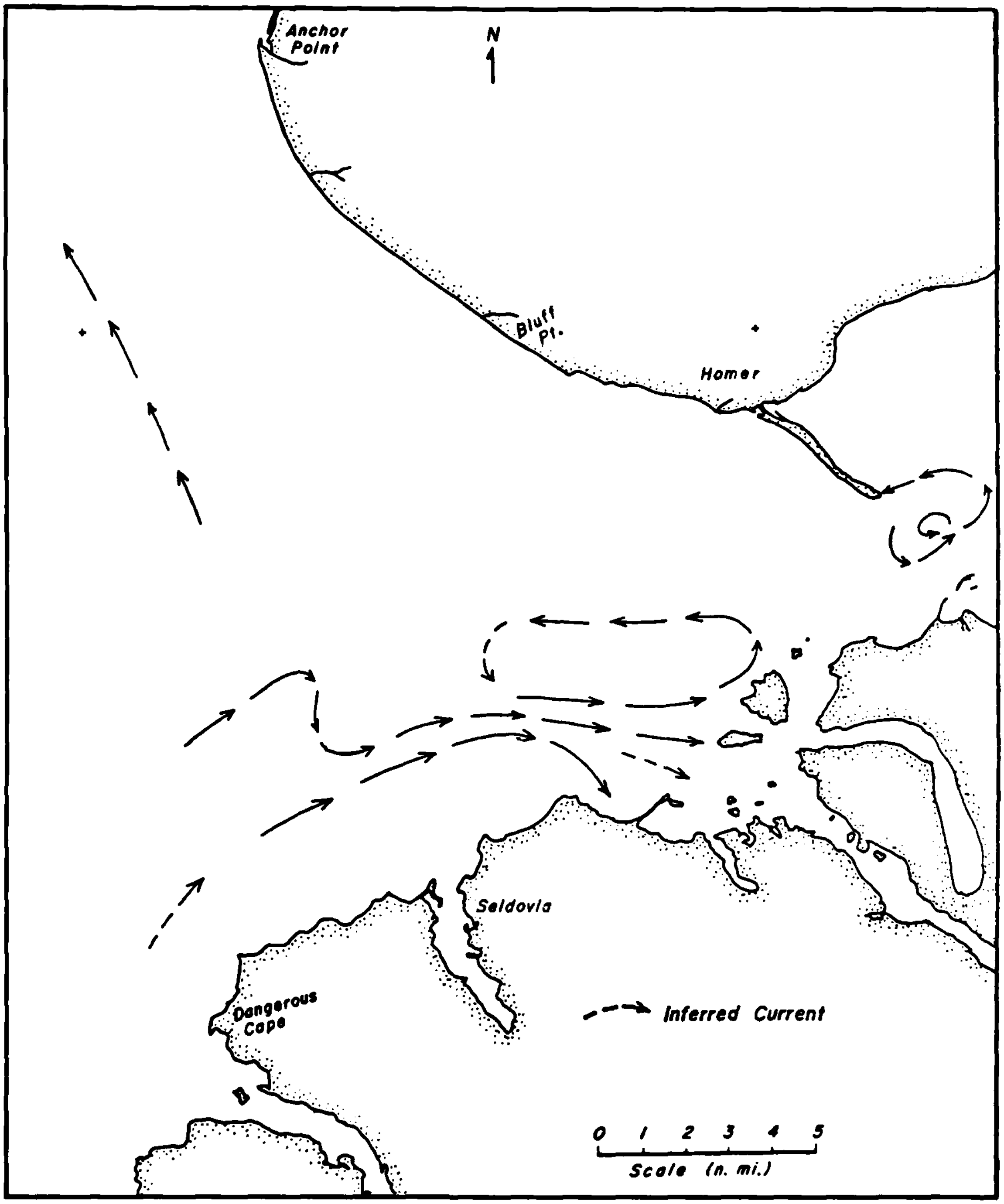

Figure 14. Surface currents during 11–17 November 1975 (from Burbank 1977).

sionally observed along the south shore. The circulation in the inner bay is comparable to that in the spring and summer, although two counterclockwise gyres reported in the inner bay were not apparent. They were probably undetectable because the sediment concentrations are too low in the winter to act as a reliable tracer, and the small number of images did not provide a complete data base.

The current along the north shore of the outer bay appeared to move southeasterly, which is opposite to that reported in the spring and sum-

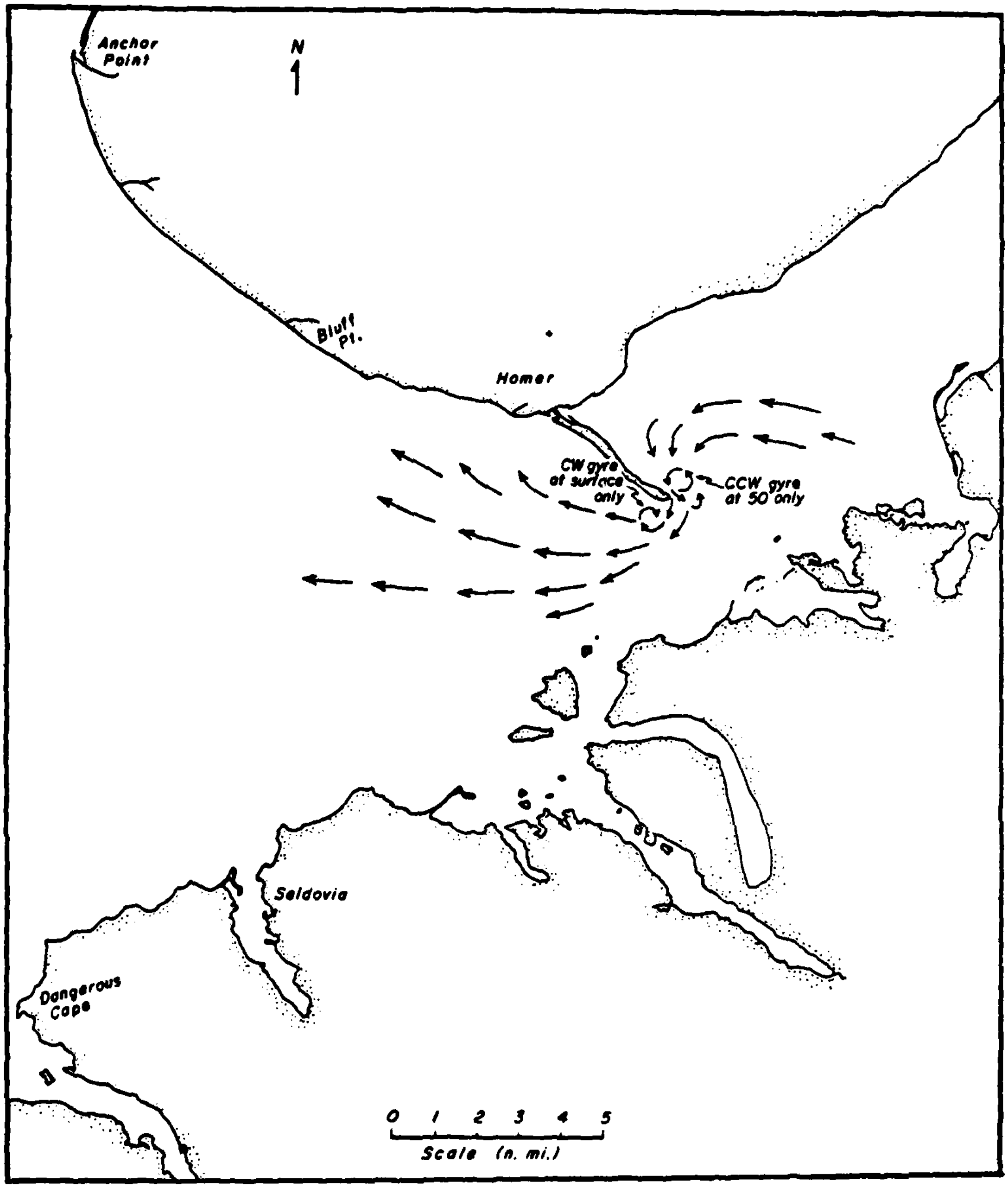

Figure 15. Surface and subsurface (50-ft depth) currents during 18–20 November 1975 (from Burbank 1977).

mer. Rip currents were also apparent along this shore. Occasionally, water appeared to enter the inner bay around the spit and along the south shore. This pattern was previously suspected but the time of its occurrence was uncertain (Bright et al. 1960).

Most of the summer circulation patterns in the outer bay, determined by previous drift card, drogue and current meter surveys and from temperature and salinity distributions, were not observed on the winter imagery. Because the surface water of the outer bay is generally much clearer year-round than that in the inner bay and because ice is usually absent, winter surface circulation patterns could be inferred for only limited areas of the outer bay.

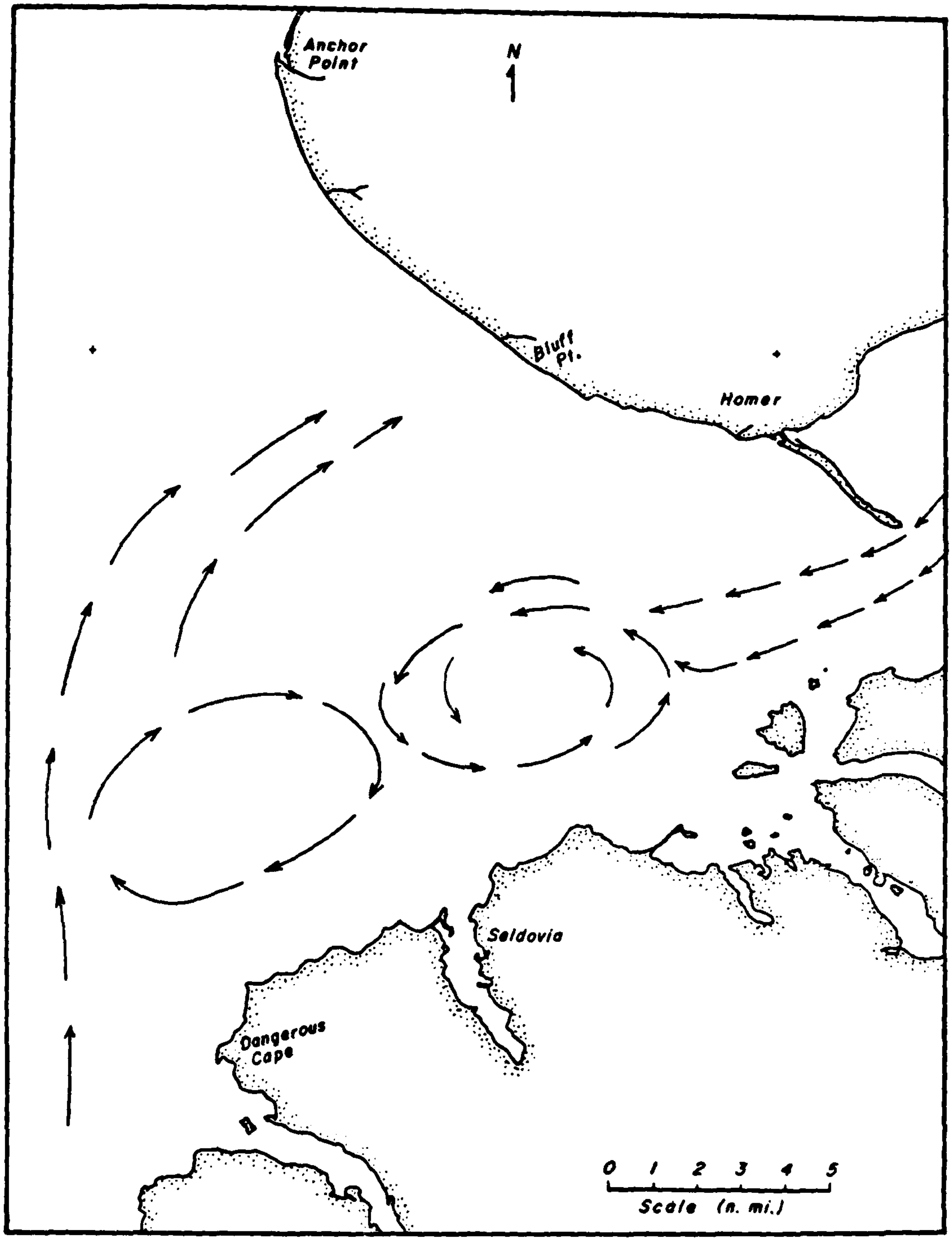

Figure 16. Surface currents during 8-14 March 1976 (from Burbank 1977).

Burbank (1977) reported surface currents for four periods included in this analysis, 11-20 November 1975, 8-22 March 1976, 8-14 April 1976 and 28 April to 6 May 1976. His results are shown in Figures 14 through 19. None of the circulation patterns he observed in the outer bay west of Yukon Island (Fig. 14-17 and 19) was apparent on the Landsat imagery. However, some of the patterns east of Yukon Island and in the inner bay were observed in the imagery or could be inferred from sediment and ice patterns observed on the imagery.

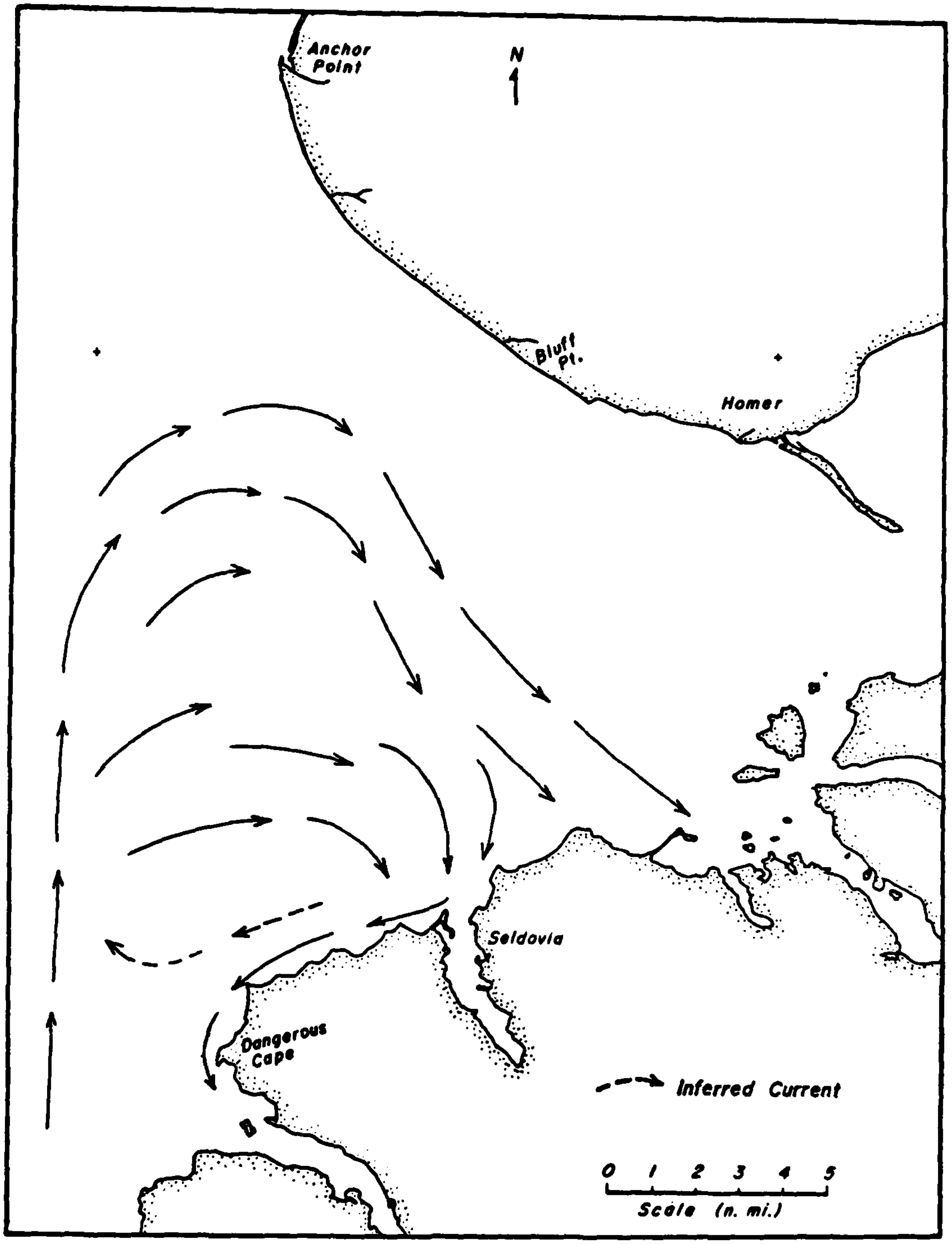

Figure 17. Surface currents during 15-22 March 1976 (from Burbank 1977).

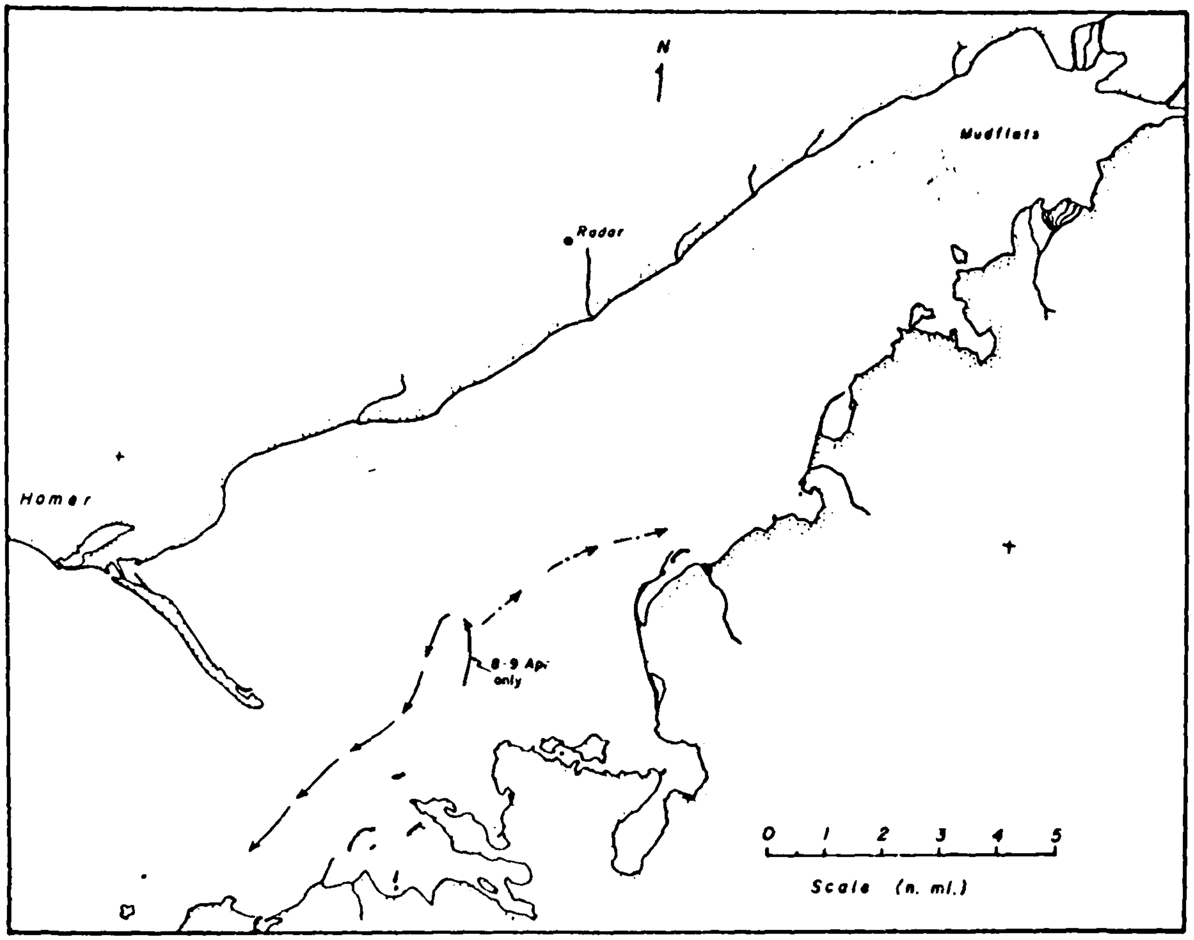

Figure 18. Surface and subsurface (100-ft depth) currents during 8–14 April 1976 (from Burbank 1977).

The inflow portion of the small counterclockwise gyre southeast of Coal Point in Figure 14 was also inferred from sediment patterns observed on imagery from 8 November 1976 (Fig. 10). The rest of this gyre was not apparent on the imagery, although the southwesterly flow past Coal Point (Fig. 15 and 16) was inferred from ice patterns on the imagery (Fig. 12 and 13).

The outflow patterns from the inner bay (Fig. 16, 18 and 19) were not apparent on the Landsat images (Fig. 13). The northeasterly currents (Fig. 19) along the middle of the southern shore of the inner bay were inferred from sediment patterns apparent on the imagery (Fig. 10 and 13).

The southeasterly current between Bluff Point and Coal Point (Fig. 10 and 13) observed on the imagery was not reported by Burbank (1977). This current pattern may result as a nearshore surface counter-current generated as surface water flows northwesterly through the outer bay farther offshore (Fig. 15 and 19). In addition, this pattern bay be initiated if the northeasterly currents in the west end of the outer bay (Fig. 16) extend to Bluff Point.

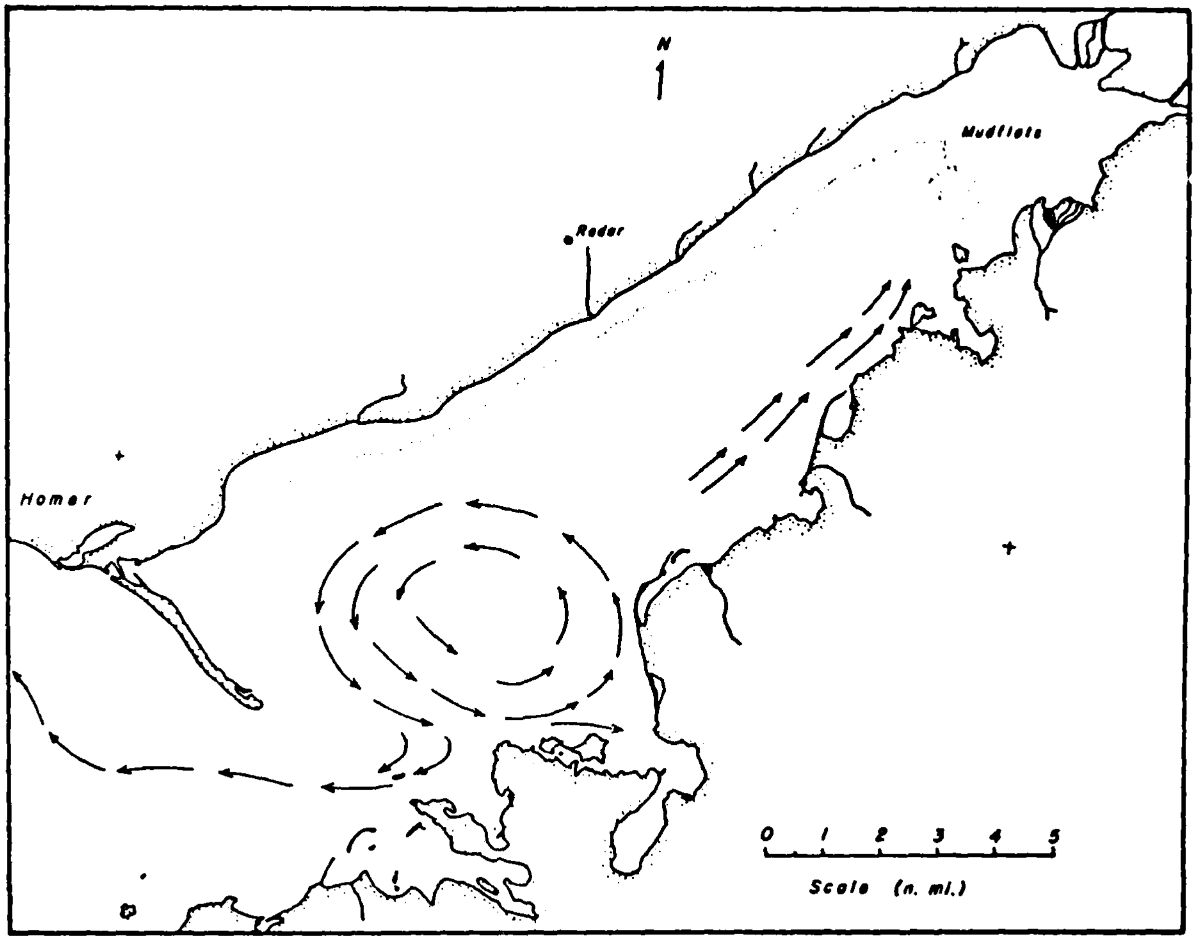

Figure 19. Surface currents during 18 April–6 May 1976 (from Burbank 1977).

CONCLUSIONS

Surface water circulation appears to be driven more by tidal forces than by wind stress. Similar circulation patterns are observed under variable wind forces. Ice movement is influenced by water stress and wind stress. Since winter winds are predominantly N to NE and inner bay water circulation is counterclockwise, ice tends to be moved southwestward along the north shore of the bay.

From the observed ice distribution and generalized circulation patterns, I expect that, if additional ice is formed due to future increased winter discharge from Bradley River, a greater ice cover will accumulate along Homer Spit and move into the outer bay by the dominant northerly winter winds and the surface currents.

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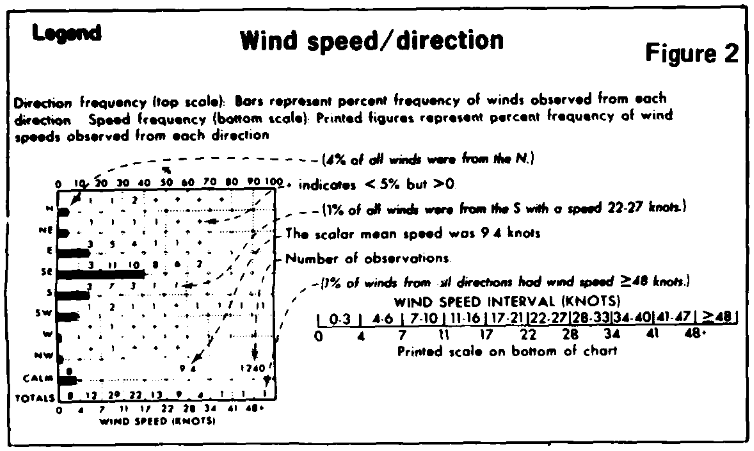
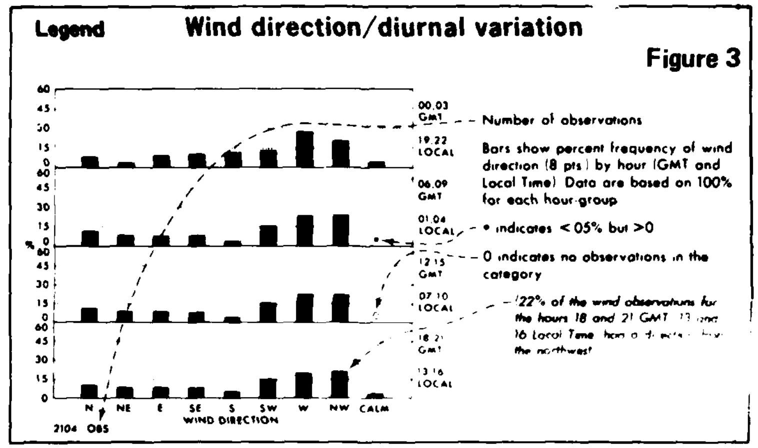
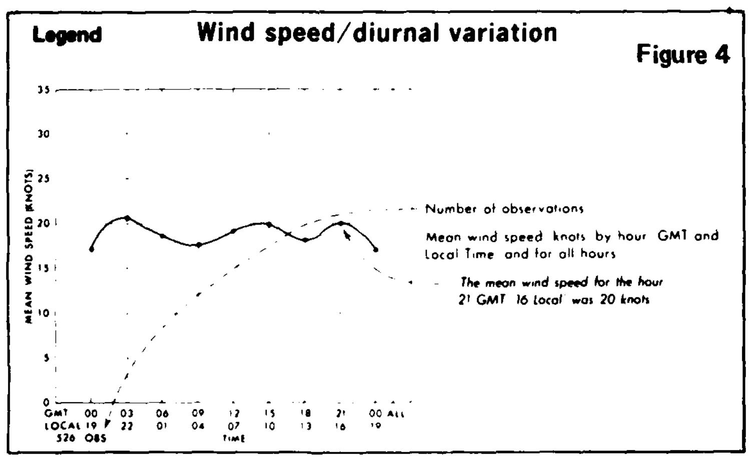
APPENDIX A: KEYS TO FIGURES 2, 3 AND 4 (FROM BROWER ET AL. 1977).







APPENDIX B: OBSERVATIONS MADE FROM USABLE LANDSAT IMAGERY.

Date	Observations*	Remarks
	1972-1973	
2 Nov 72	NAI, NOP	
3 Nov 72	NAI, NOP	
4 Nov 72	NAI, NOP	
8 Mar 73	Possible ice stringer from Coal Pt. into OB; Possible ice accumulation in Coal Bay	H and CC too heavy for other observations
15 Apr 73	NAI, NOP	CC over south OB
	1973-1974	
16 Nov 73	NAI, NOP	CC over OB
3 Mar 74	NAI, NOP	CC over IB
4 Mar 74	Ice on tidal flat at head of IB; ice stringer in southeast direction north of HS; NOP in OB	CC over north OB
22 Mar 74	Ice on tidal flat at head of IB	CC obscures most of IB and all OB
26 Apr 74	NAI, NOP	
27 Apr 74	NOP	Partial CC
	1974-1975	
10 Nov 74	NAI	Suspended sediment variations along SW side of HS; north/south streaking in IB
12 Nov 74	NAI, NOP	Partially obscured by H and CC
10 Feb 75	NAI except near Anchor Pt, NOP	
27 Feb 75	NAI, NOP	Mostly obscured by H and CC
28 Feb 75	NAI, NOP	
16 Mar 75	NAI, NOP	Tidal flats at head of IB appear snow-covered
3 Apr 75	NAI, NOP	Tidal flats still snow-covered
12 Apr 75	NAI Sediment pattern in middle of IB	CC along north shore of OB
	1975-1976	
26 Jan 76	Ice buildup in Coal Bay	CC and H obscures most of Ib and OB
24 Feb 76	NOP Fast ice in Coal Bay; NAI elsewhere in OB	
6 Apr 76	NAI, NOP Suspended sediment patterns southeast of Bluff Pt.	Flats snow covered
8 Apr 76	NAI, NOP in OB	Partially CC and H
24 Apr 76	NAI Longshore drift apparent from Bluff Pt. to Coal Pt; NOP	

	1976-1977	
8 Nov 76	NAI; suspended sediment pattern around HS and southeast of HS along south shore	CC over upper IB
10 Nov 76	NAI, NOP in OB	
25 Feb 77	NAI; suspended sediment patterns in IB and north shore of OB	
2 Apr 77	NAI, NOP	Scattered CC obscures IB and OB
	1977-1978	
4 Nov 77	NAI, NOP	IB and OB partially obscured by CC
5 Nov 77	NAI, NOP in OB	
2 Feb 78	NAI, NOP	
10 Mar 78	NAI Suspended sediment patterns in IB	Most of IB and OB obscured by CC
18 Mar 78	NAI at head of IB	OB and lower IB obscured by CC
5 Apr 78	NAI, NOP	CC masks part of IB
7 Apr 78	NOP, NAI in OB and southern IB	Partially masked by CC
	1978-1979	
7 Nov 78	NAI Suspended sediment patterns in IB	
8 Nov 78	NAI, NOP Suspended sediment patterns on south side of HS	
16 Nov 78	NAI, NOP	
17 Nov 78	NAI, NOP	Most of bay obscured by CC
5 Feb 79	Ice in Coal Bay; possible ice floes in head of IB; IR imagery shows colder water along north part of IB and OB around HS; NOP	
6 Feb 79	Ice along north shore of IB and in Coal Bay; NOP	
7 Feb 79	Ice in Coal Bay; NOP	Much of IB and OB masked by CC
14 Feb 79	Ice along north shore of IB; shorefast ice in Coal Bay out to Coal Pt.; NOP	
23 Feb 79	Ice along north shore of IB; degrading shorefast ice in Coal Bay; shore ice at head of IB	
15 Mar 79	NOP; NAI; Suspended sediment patterns in IB	OB masked by CC and H
23 Mar 79	NAI, NOP	
11 Apr 79	NAI, NOP	
	1979-1980	
31 Jan 80	NOP	IB and OB obscured by CC
18 Feb 80	NAI Suspended sediment at head of IB	
14 Apr 80	NAI, NOP	IB obscured by CC

* NAI = No apparent ice
NOP = No observable circulation patterns
CC = Cloud covered
H = Haze

OB = Outer bay
IB = Inner bay
HS = Homer Spit

APPENDIX C: SELECTED LANDSAT IMAGES USED TO MAKE OBSERVATIONS AND INTERPRETATIONS OF SURFACE WATER PATTERNS AND ICE DISTRIBUTION. (Some of the patterns and features observable on the original transparencies are not as apparent on these copy prints.)

Figure C1. Landsat-1, MSS7, 8 Mar 73, I.D. 1228-20464.

Figure C2. Landsat-1, MSS5, 4 Mar 74, I.D. 1589-20470.

Figure C3. Landsat-1, MSS5, 26 Apr 74, I.D. 1642-20401.

Figure C4. Landsat-1, MSS5, 10 Nov 74, I.D. 1840-20335.

Figure C5. Landsat-2, MSS5, 12 Apr 75, I.D. 2080-20343.

Figure C6. Landsat-2, MSS5, 14 Feb 76, I.D. 2388-20430.

Figure C7. Landsat-2, MSS5, 6 Apr 76, I.D. 2440-20295.

Figure C8. Landsat-2, MSS7, 24 Apr 76, I.D. 2458-20292.

Figure C9. Landsat-2, MSS5, 8 Nov 76, I.D. 2656-20234.

Figure C10. Landsat-2, MSS5, 25 Feb 77, I.D. 2765-20250.

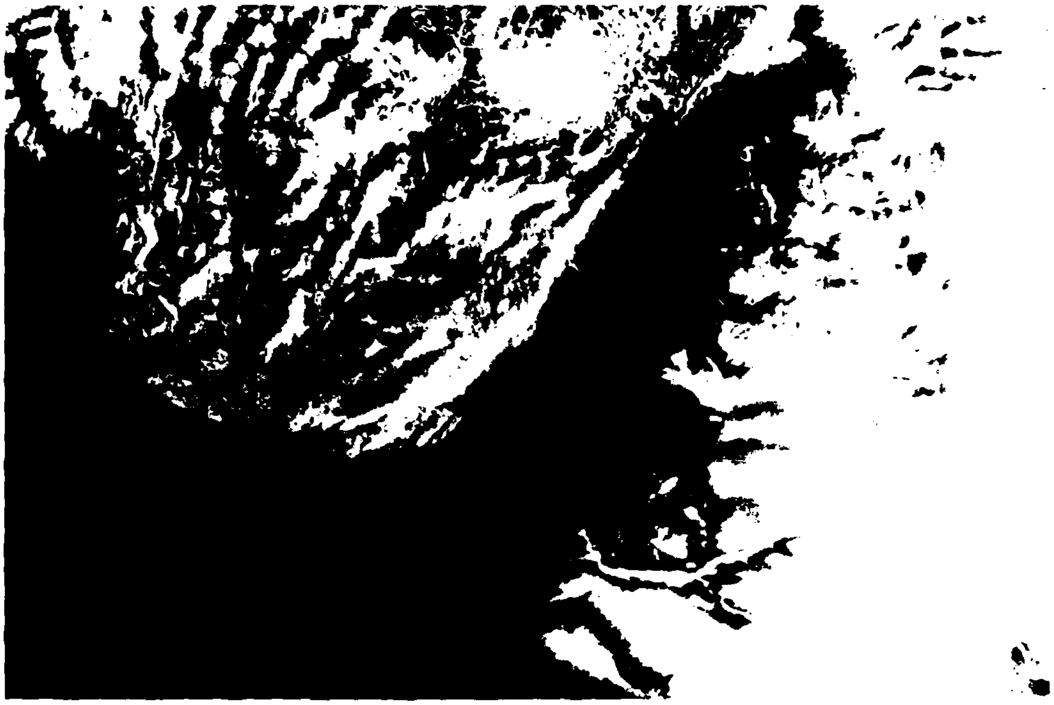


Figure C11. Landsat-2, MSS5, 10 Mar 78, I.D. 21143-20125.

Figure C12. Landsat-3, MSS5, 5 Feb 79, I.D. 30337-20352.

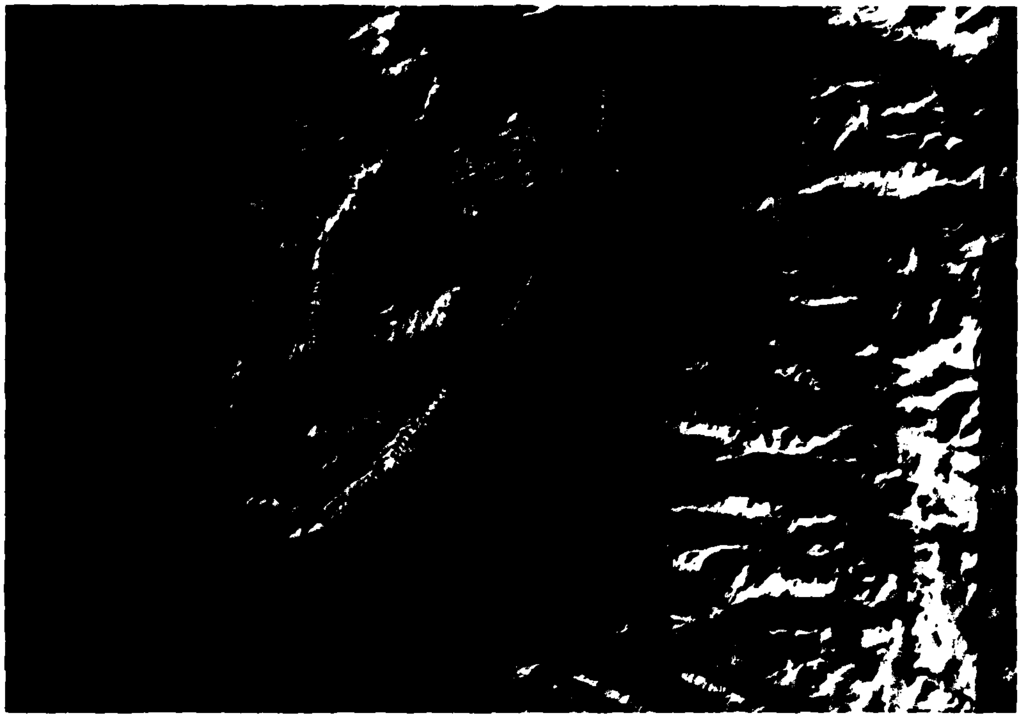


Figure C13. Landsat-3, MSS5, 6 Feb 79, I.D. 30338-20411.

Figure C14. Landsat-3, RBV-D, 7 Feb 79, I.D. 30339-20464.

Figure C15. Landsat-2, MSS5, 14 Feb 79, I.D. 21484-20225.

Figure C16. Landsat-3, MSS5, 23 Feb 79, I.D. 30355-20352.

Figure C17. Landsat-3, MSS5, 15 Mar 79, I.D. 30375-20463.

Figure C18. Landsat-3, RBV-C, 18 Feb 80, I.D. 30715-20301.

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Gatto, Lawrence W.
Ice distribution and winter surface circulation patterns, Kachemak Bay, Alaska. Hanover, N.H.: Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1981.
vi, 50 p., illus., 28 cm. (CRREL Report 81-22.)
Prepared for U.S. Army Engineer District, Alaska, by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory.
Bibliography: p. 26.
1. Ice. 2. Kachemak Bay. 3. Oceanography. 4. Remote sensing. 5. Surface circulation. 6. Suspended sediments. I. United States. Army. Corps of Engineers. II. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. III. Series: CRREL Report 81-22.

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